TAMPERE UNIVERSITY OF TECHNOLOGY

NILLO HALONEN

PRODUCT LIFE-CYCLE DISPOSITION MODEL
- DISPOSITION CONCEPTUALISING FOR DESIGN SCIENCE

Master of Science Thesis

Prof. Asko Riitahuhta has been appointed as the examiner at the Council Meeting of Faculty of Automation, Mechanical and Materials Engineering on May 9th, 2012

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
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Several companies in the Finnish manufacturing industry produce partly configurable products that include one-of-a-kind components. One-of-a-kind components cause challenges within companies, as opposed to fully configurable products, which include only standard and configurable components. Identifying and managing these challenges is hard, as the subject of product structure affecting the product’s life-cycle such as order-delivery process is complex and requires a holistic approach.

This research aims to provide a description of differences of characteristics and behaviour between partly configurable product structures and fully configurable product structures, in a chosen scope of product life-cycle phases. This is done by developing a conceptual framework, Product Life-cycle Disposition Model (PLDM), which is an explanatory model to describe dispositions and how to manage them in order to achieve a company’s targets. The research applies Design Research methodology in the research process. The initial version of the model is constructed based on the literature review, theory basis and state of the art around Design Science and Systems Engineering. The explanatory model is demonstrated and further developed in a case study with a company from the Finnish manufacturing industry. In the case study, the current company’s partly configurable product and its captured relevant dispositions are compared to a scenario of fully configurable product. From the overall analysis of the dispositions results and recommendations are drawn.

The case study indicates that the PLDM framework resembles the real world situation in business and the challenge the manufacturing industry currently faces in Finland. Partly configurable product structures are a good example of the effect the product structure has to the overall product life-cycle. The results of the case study examining the company's product indicated that the order-specific product structures caused invalidity of the information in three chosen phases of the product's life-cycle. The results also represented recommendations for actions to solve the problems following the PLDM framework. The recommended actions were directed to changing the product’s life-cycle’s characteristics.

This research concludes the PLDM is comprehensive in relation to the chosen theories and state of the art in Design Science and Systems Engineering. It contributes to the Design Science by providing a cyclic model to develop the product’s characteristics and product’s life-cycle system towards its requirements and targets, derived from product’s life-cycle. The novelty of the PLDM is that it uses a Flow model to depict the information, work, material and control flows in the life-cycle process. The PLDM provides a conceptual framework for the manufacturing industry to develop their integrated product and process systems. The PLDM is seen as part of a broader research area, which aims to introduce a supportive tool for consultation purposes.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Konetekniikan koulutusohjelma
HALONEN, NILLO: Tuote-elinkaaridispositiomalli – Dispositiokonseptointi tuotekehityksessä
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Useat yritykset Suomen valmistavassa teollisuudessa tuottavat osittain konfiguroitavia tuotteita, jotka sisältävät uniikkeja komponentteja. Nämä uniikit komponentit tuovat yrityksiin haasteita, suhteessa täysin konfiguroitaviin tuotteisiin, jotka vastaavasti koostuvat pelkästään standardeista ja konfiguroitavista komponenteista. Yrityksille näiden haasteiden tunnistaminen ja hallitseminen on vaikeaa, sillä tuoterakenteiden ja tuotteen elinkaaren vaiheiden, kuten tilaustoimitusprosessin, väliset riippuvuudet ovat kompleksisia ja vaativat kokonaisvaltaista lähestymistä.

Tämän työn tavoitteena on kuvata ominaisuus- ja käyttäytymiseroja osittain konfiguroitavien ja täysin konfiguroitavien tuoterakenteiden välillä, rajatussa määrässä tuotteen elinkaaren vaiheita. Työ on osana laajempaa tutkimusta, jossa tavoitteena on kehittää päätöstä ja ymmärrystä tukeva työkalupaketti konsultaatiotarkoituksiin. Työ on toteutettu kehittämällä Tuote-elinkaaridispositiomalli (Product Life-Cycle Disposition Model, PLDM), joka toimii selitysmallina kuvaamaan tuotteen ominaisuuksien ja tuotteen elinkaaren välisiä riippuvuuksia eli dispositioita. PLDM toimii myös prosessinkuvauksena, missä sekä tuotetta että elinkaaren aikaisia prosesseja voidaan kehittää samanaikaisesti. Tutkimusprosessi soveltaa Design Research -metodologiaa. Alustava versio mallista luodaan kirjallisuusselvityksen pohjalta, jossa käydään läpi relevantti teoriapohja ja tämän hetken vallitseva tutkimus tuotekehityksen ja systeemitekniikan ympäriltä. PLDM esitellään ja testataan käyttämällä tapaustutkimusta, jossa hyödynnetään tietoja suomalaisesta valmistavan teollisuuden yrityksestä. Tapaustutkimuksessa yhden yrityksen tuotteen oleelliset tuoteominaisuudet selvitetään, sekä mallinnetaan tuotteen elinkaaren virtauselementit, informaatio-, työ-, materiaali- sekä kontrollivirrat. Tämän jälkeen kuvataan kohdistetusti dispositioita, joita verrataan elinkaariskenaarioon täysin konfiguroitavassa tuotteessa. Dispositioiden analyyseistä johdetaan tulokset ja suositukset yritykselle jatkotoimenpiteisiin.

Tapaustutkimus osoittaa, että PLDM-viitekehys todentaa käytännön tilannetta teollisuudessa ja niitä haasteita, mitä valmistava teollisuus Suomessa kohtaa. Osittain konfiguroitava tuoterakenne on hyvä esimerkki tuotteen ominaisuuksien vaikutuksesta tuotteen koko elinkaareen. Tapaustutkimuksen tulokset osoittivat, että muun muassa informaatiovirran puuttuminen muutamassa elinkaaren vaiheessa johtui tilauskohtaisesta tuoterakenteesta. Dispositioiden analysoimisesta johdettiin myös yritykselle toimenpiteet ongelmien ratkaisemiseksi noudattaen PLDM-viitekehystä.

Johtopäätöksenä voidaan todeta, että PLDM noudattelee valittua teoriapohjaa ja viimeisintä tutkimusta tuotekehityksessä ja systeemitekniikassa. Tutkimus osallistuu tuotekehityksen tutkimukseen tarjoamalla syklisen mallin integroituun tuotteen ja tuotannon kehittämiseen hyödyntämällä tuotteen elinkaaressa virtausmallia. PLDM tarjoaa selitys- ja toimenpidemallin valmistavalle teollisuudelle heidän integroidun tuotteen- ja tuotannon kehitykseen.

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This thesis was done for the Department of Production Engineering at Tampere University of Technology (TUT). The thesis started in January 2012 and was finished by the end of November 2012.

It has been a great journey from the beginning to the very end working. Valuable lessons have been learned along the way, even though the thesis started with a slightly different topic and changed its focus and objectives several times during the working process, I would not change a day.

I would like to express my gratitude for several people that have been supporting this journey. I would like to thank my supervisor, Dr. Tero Juuti for your guidance and motivation throughout the working process. Without you this work would not have been as agile as it was. The projects I’ve been involved with, and the first business trips I have taken part of during the thesis process, have been a thrilling and memorable experiences. I also want to thank Dr. Timo Lehtonen for giving advice and vital knowledge about the research I was working on. Great gratitude goes also to my Professor, and appointed examiner, Asko Riitahuhta for your instructions in improving the thesis. In addition, I like to thank the rest of the IPPD team Pasi Luostarinen, Jarkko Pakkanen and Mikko Vanhatalo. This team really has the potential for empowerment without limits.

Many thanks go to my brother-in-law, Luke Harriman and my sister, Henna Halonen. Your contribution in helping me to improve the linguistic fluency of the thesis was invaluable. The writing process has reached a completely new level with your help. The discussions with you, Luke, have been interesting and have helped me find the thread when it was most needed.

Most importantly I would like to thank my family, my girlfriend and my friends. You have been my foundation before I started my trek at TUT and every day since. You have been beside me even on the steep climbs and sudden drops. You are the most valuable things I have.

Final words in Finnish: Kevyesti meni vaikkei siltä tuntunut!

Tampere 21.11.2012

Nillo Halonen

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ABBREVIATIONS AND NOTATIONS

BOL	Beginning of (Product) Life-cycle
CPM	Characteristics-Properties Model
CSL	Company Strategic Landscape
DFX	Design For X
DMM	Domain Mapping Matrix
DiMo	Disposition Modelling, tool developed in Tampere University of Technology
DRM	Design Research Method
DS 1	Descriptive Study 1 (part of DRM)
DS 2	Descriptive Study 2 (part of DRM)
DSM	Design Structure Matrix
EC	External Conditions
EOL	End OF (Product) Life-cycle
GEBOM	Generic Engineering Bill of Materials
GST	General Systems Thinking
HST	Hard Systems Thinking
HOQ	House of Quality
IPPD	Integrated Product and Production Development
MDM	Multi-Domain Matrix
MOL	Middle of (Product) Life-cycle
NPD	New Product Development
RC	Research Clarification (part of DRM)
PDD	Product Driven Development
PLDM	Product Life-cycle Disposition Model
PLM	Product Life-cycle Management
PS	Prescriptive Study (part of DRM)
QFD	Quality Function Deployment
SCM	Structural Complexity Management
SE	Systems Engineering
SSM	Soft Systems Methodology
SST	Soft Systems Thinking
TUT	Tampere University of Technology

1. INTRODUCTION AND MOTIVATION

Configurable products are common practice in the Finnish manufacturing industry. In today's global climate configurability is a competitive and widely accepted way to fulfil a wide range of customer requirements and to have the advantages of repetition of similar products and components (Juuti 2008). However, this is not as simple as it would seem.

Generally, a company approaches a configurable product structure from two directions; from a mass product perspective, or from a project-oriented, one-of-a-kind products starting point (Tiihonen et al. 1996) (see figure 1.1). For example, a change from one of kind products to configurable products can be a long and challenging process, which requires a lot of development in the company's overall operations. In addition, a whole configuration support system and a product knowledge reuse system have to be developed in order to manage and maintain configurable products.

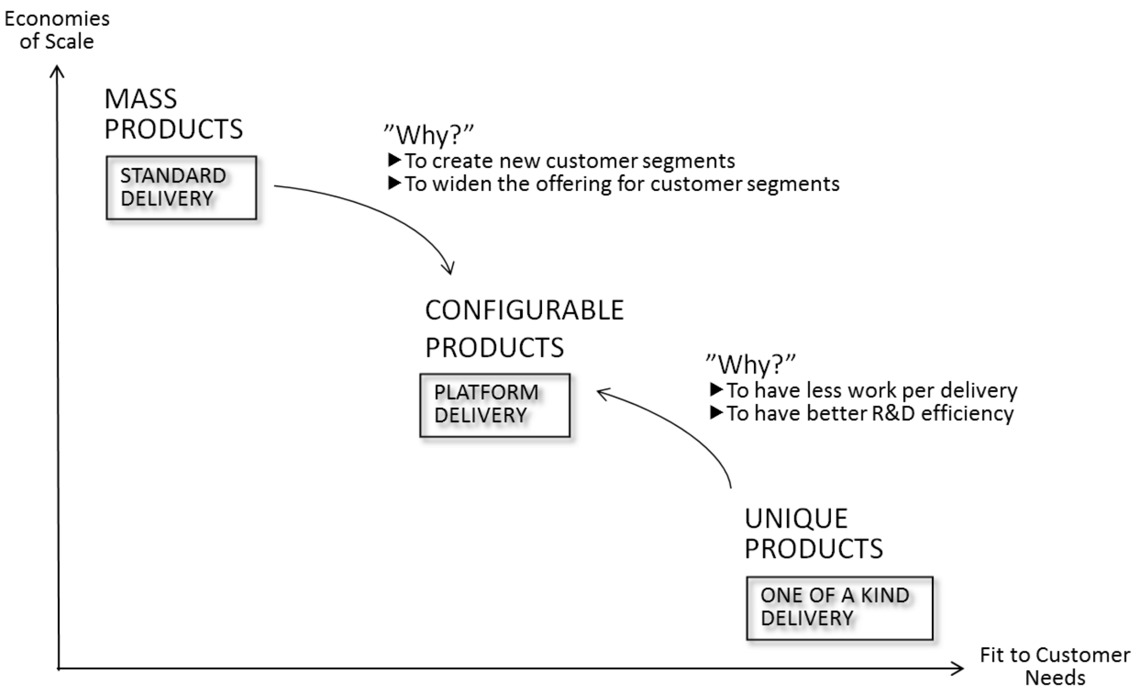


Figure 1.1. *A shift over to configurable paradigm.* (altered from Juuti & Lehtonen 2006)

Integrated Product and Production Research Group (IPPD) from Tampere University of Technology, led by Professor Asko Riitahuhta, has a strong research background in product structures and design methods, especially in product modularisation and configuration. The research group has worked in projects specifically involving partly configurable product structures. According to the group's experience, many companies in the Finnish manufacturing industry are still in the middle of this paradigm shift from order-specific product structure to fully configurable product structures. The result is a partly configurable product structure, which at the same time includes configurable components and one-of-a-kind (order-specific) components. Partly configurable product structures have not been the focus of any larger scale research, and in any currently available research, it has not been distinguished from the configurable products category.

Also, according to the experience of IPPD research group, currently companies are expecting the same advantages of the industry activities through repetition with partly configurable product structures, as it would be possible with fully configurable products. There is clearly conflicting relationships between the expectations and the actual behaviour in the product's life-cycle. The inadequate knowledge of partly configurable products and their special requirements appear to be the reason for this.

The research group has identified that companies in the manufacturing industry acknowledge that certain steps are required to realise an intention towards a ready, physical, desired product. Furthermore, companies understand that information is required to achieve these steps. What seems to be challenging for the companies is to recognise the inter-relationship and interaction between product structure and product life-cycle. These relationships are called dispositions. This seems to be also one of the reasons for the unawareness of the challenges that should be considered with partly configurable product structures. As long as these dispositions remain unrecognised, actions to overcome challenges facing partly configurable products cannot be undertaken. The term disposition is often linked to Olesen's (1992) definition of dispositional mechanisms however, the meaning is different in this thesis as will be shown later.

This thesis aims to provide an explanatory model for understanding these inter-relationships and interactions between product structure and product life-cycle. It is a conceptual framework to explain integrated product and production development system for the manufacturing industry. By doing so, the model will also open a conversation about the challenges companies are facing due to partly configurable product structures.

1.1. Context

This study exists as part of a wider research area by the IPPD research group pertaining to integrated product and production development. This thesis develops an initial conceptual framework with the potential to inform consultation processes with manufacturing businesses to help outline and understand the impacts of decision making and create design rationale. Its purpose will be realised in the area of product and production development both in science and in practice through further research and continued to industry application.

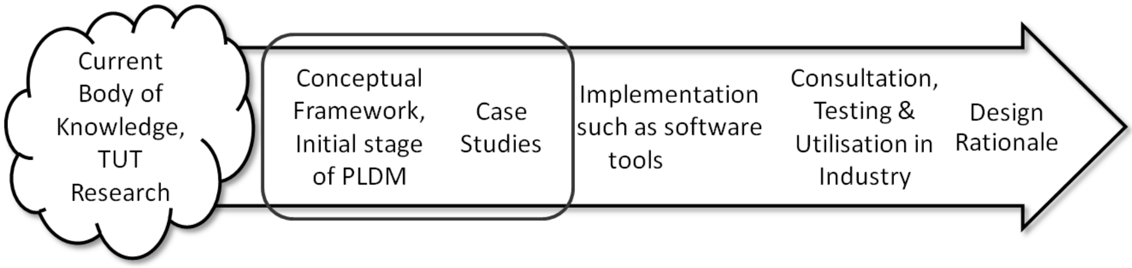


Figure 1.2. *Contribution of the thesis within the wider research area.*

Figure 1.2 shows a roadmap of the wider research area. As indicated by the annotation box above, this thesis relates to the first two stages of this research by developing the conceptual framework and testing it through a case study.

1.2. Objectives

The primary aim of this thesis is:
Description of differences of characteristics and behaviour between partly configurable product structures and fully configurable product structures, in a chosen scope of product life-cycle phases.

To achieve this aim, this thesis has two main objectives. These objectives are the following:

1. **Introduction of a concept for disposition modelling using information, work and control flows.**
2. **Capture of the characteristics, dispositions, and properties of partly configurable product structure and fully configurable product structure.**

These objectives are derived from the experience of the researchers in the Department of Production Engineering at TUT and are natural successors to the previous work done at TUT.

First of the objectives, a concept for the disposition model, will be gathered from a literature review and from the previous work done in the area of Design Science, dispositional thinking and life-cycle modelling. This objective will have a significant influence from the previous work done in the integrated product and production development (IPPD) research team in the Department of Production Engineering at TUT. It will be tested and further developed in a case study. The disposition model is a practical framework to support decision making during concept development phase in design process. The outcome of this objective is an initial concept for the model. In the initial model only one of the elements in flow model will be used as demonstration. The chosen flow is information flow.

The latter of the objectives, a capture of product characteristics, dispositions, and behaviour between partly configurable and fully configurable products, will utilise the theory and methodologies gathered in the area of product configuration and modularisation when using the disposition model in practice. Product configuration and modular system knowledge thrives from the past work done by Professor Asko Riitahuhta, Doctor Tero Juuti, Doctor Timo Lehtonen and the IPPD research team in Tampere University of Technology. In the comparison, the different effects in the cases of fully configurable product and partly configurable product will be analysed. As an outcome, results and conclusions from the examination will be presented. These conclusions will also represent an example of practical results gained from the disposition model.

1.3. Research questions

The objectives are transformed into the following research questions. These will guide the writing process to give an answer to the objectives.

The first objective is transformed in to two questions:

- **What kind of elements a disposition model consists of?**
- **How is a disposition model implemented in practice?**

The second objective is addressed using the following question:

- **What is the difference between a fully configurable product family and partly configurable product family?**

1.4. Research scope

The needs for this research were identified through the on-going work of the IPPD research group at TUT. The scope of the research was chosen to compliment the wider research area, of the IPPD research group in the chapter 1.1.

IPPD research group is primarily involved with product development research projects within the Finnish manufacturing industry, and therefore this thesis pertains to Design Science and Systems Engineering. All of the theories and state of the art can be traced back to these two broader fields.

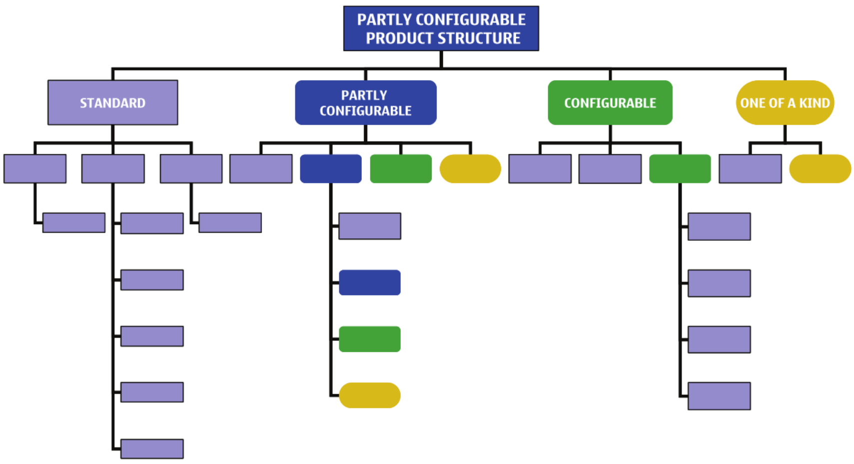


Figure 1.3. *Division of product structures, the case of partly configurable product structure.* (Attained from Juuti & Lehtonen 2006).

In product development, this thesis focuses on partly configurable and fully configurable product structures. A partly configurable product structure (figure 1.3) consists of standard, partly configurable, configurable and one-of-a-kind (order-specific) components. This decision came from the IPPD research group, and was determined to be a good, demonstrable case for the size of a Master of Science thesis.

This thesis concentrates on the development processes of existing products, or brownfield products. However, the possibility of utilising the model in new product development is not excluded from future target of application and research.

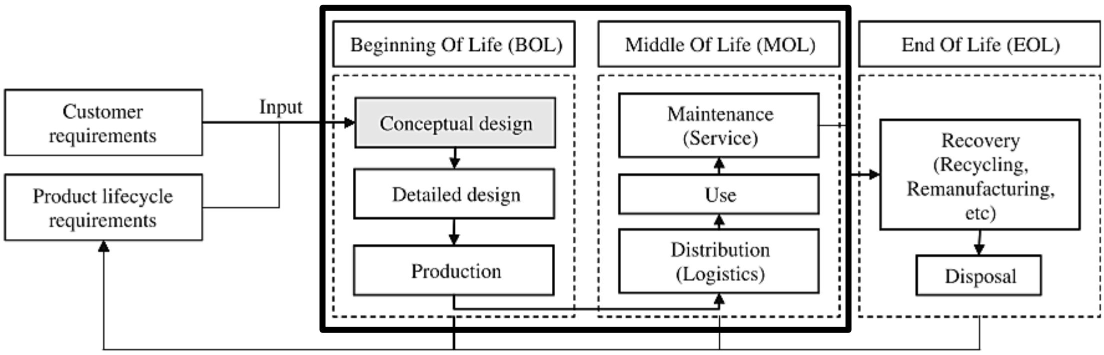


Figure 1.4. *Product Life-cycle divided into three phases. Black annotation box indicates the area of focus* (Dimitris Kiritsis et al. 2003, cited in Shin et al. 2010)**.**

This research also investigates product life-cycles (figure 1.4), however it is limited to Beginning of Product Life-cycle (BOL) and Middle of Life-cycle (MOL) phases. It also includes general product life-cycle phases, from order to delivery and from utilisation to maintenance services. This was due to the case study, which only provided analysis within these life-cycle phases.

1.5. Structure of the thesis

In the thesis, the research approach is represented first, and describes the chosen research method and classifies it in relation to other approaches. Then the process for the formulation of research questions is described followed by the description of selecting relevant theories and state of the art. Then the chosen theory basis and relevant state of the art, a case study, the results and recommendations of the case study, discussion, and conclusion are described.

2. RESEARCH APPROACH

This chapter gives an overview of the research method used in this thesis. Literature for references will later be described.

This thesis follows the Design Research Methodology (DRM), guidelines, a common research methodology used in design. First a classification of the research approach is identified, the research methodology will be explained and then a more detailed approach within the DRM will be described.

2.1. Classification of research approach

A classification in which research work is divided between descriptive and normative, whereas in theoretical and empirical, was first presented by Neilimo and Näsi (1980) and was later extended by Kasanen et al. (1993) (see Koho 2010). The classification identifies five different fundamental research approaches which are located in between two perpendicular axes. These axes are descriptive-normative and theoretical-empirical. Figure 2.1 shows the five approaches marked on in the axes, which are conceptual, nomothetical, action-oriented, decision-oriented and constructive.

	Theoretical	Empirical
Descriptive	Conceptual approach	Nomothetical approach
		Action-oriented approach
Normative	Decision-oriented approach	Constructive approach

Figure 2.1. *Classification of research approaches* (Kasanen et al. 1993).

Descriptive research describes the object of research and answers questions such as ”how things are” and ”why things act like they act”(Lukka 1991). Normative research contributes to decision-making, answering questions such as “how should things be” and “what should be done” (Lukka 1991). Moving to the other axis, theoretical research relies on previous research and empirical research commonly involves implementations of results in practical use or demonstrations of results’ usability in practice, however this will not play a significant part of the thesis (Lukka 1991; Kasanen et al. 1993, cited in Koho 2010).

This thesis is classified as a conceptual approach, as it aims to construct a conceptual framework of a model using available theories and state of the art.

2.2. Design research methodology (DRM)

DRM was developed by Lucienne Blessing, Amaresh Chakrabarti and Ken Wallace in 1991 and further developed to holistically suit the design research needs (Blessing & Chakrabarti 2009). According to Blessing & Chakrabarti (2009), the three main drivers that motivated the development of DRM were:

- Lack of overview if research already existed
- Lack of use of results in practice
- Lack of scientific rigour

The biggest contribution of DRM is addressing the lack of scientific rigour. DRM provides a framework to support a more rigorous approach in order for design research to become more effective and efficient. (Blessing & Chakrabarti 2009)

DRM includes a set of supporting methods and guidelines for doing design research. Because DRM has been solely established for the purpose of design research, the objectives are consistent and aligned with the aims of this thesis. See figure 2.2 for aims, objectives and facets of design research.

Blessing & Chakrabarti (2009) identify two main objectives for design research; the formulation and validation of models and theories about phenomenon of design with all its facets and, the development and validation of support founded on these models and theories. Both objectives aim to improve design practice in many industries including management and education. (Blessing & Chakrabarti 2009.)

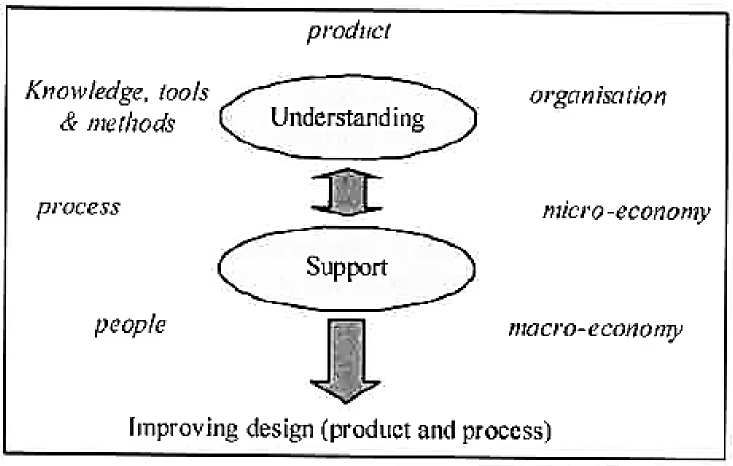


Figure 2.2. *Aim, objectives and facets of design research* (Blessing & Chakrabarti 2009).

Generally the DRM process consists of four stages, **Research Clarification (RC), Descriptive Study 1 (DS 1), Prescriptive Study (PS)** and **Descriptive Study 2 (DS 2)** ((Blessing et al. 1992; Blessing et al. 1995, cited in Blessing 2009). The DRM framework is illustrated in these four stages in figure 2.3.

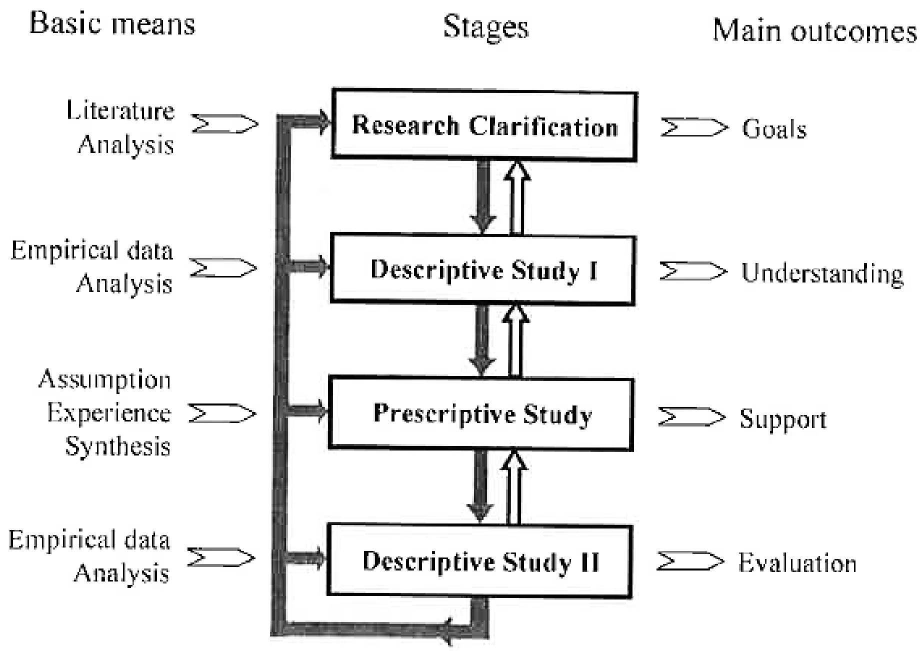


Figure 2.3. *DRM framework* (Blessing & Chakrabarti 2009).

RC is the first phase of DRM during which researchers try to find evidence to support their assumptions and to formulate a realistic and useful research goal. Also, focus of the research is realised along with research problems, research questions and hypotheses. RC commonly includes literature reviews and analysis and it is during this stage the relevant disciplines and areas of literature are chosen. Based on the findings during RC, initial descriptions of the existing situation and desired situation are developed. A preliminary set of assessment criteria is also developed to measure outcomes. Finally, RC provides a scope for later stages to fulfil their requirements. (Blessing & Chakrabarti 2009.)

DS 1 stage continues from RC, reviewing the literature for more influencing factors by investigating in more detail the initial description of the existing situation and hence, gain more understanding of the current situation. DS 1 can also include empirical data analysis if necessary to support the literature review. An important objective of this stage is to clarify in more detail the factors that influence the criteria and complete a reference model providing the basis of the next stage, PS. (Blessing & Chakrabarti 2009.)

PS determines the key factors to be addressed in order to improve existing situation. During PS an impact model is finalised and intended support is identified. The support addresses the key factors in a systematic way and includes initial evaluation of the actual support. The evaluation determines whether to proceed to DS 2 and evaluate the effects of the support. Finally, during PS an evaluation plan is outlined developed as a starting point for the final stage, DS 2. (Blessing & Chakrabarti 2009.)

The focus of DS 2 is to evaluate whether the outcomes have the expected, desired behaviour. This stage also includes justification of whether the support contributes to successful attributes, to successful evaluation and whether the impact model is tenable.

Finally, during DS 2 a significant objective is to identify necessary improvements to the concept and context of the support and to evaluate the accuracy of the reference model. (Blessing & Chakrabarti 2009.)

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based →	Comprehensive		
2. Review-based →	Comprehensive →	Initial	
3. Review-based →	Review-based →	Comprehensive →	Initial
4. Review-based →	Review-based →	Review-based → Initial/ Comprehensive	Comprehensive
5. Review-based →	Comprehensive →	Comprehensive →	Initial
6. Review-based →	Review-based →	Comprehensive →	Comprehensive
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Figure 2.4. *Types of research methods in DRM* (Blessing & Chakrabarti 2009).

DRM is essentially comprehensive but does not necessarily mean that all of the stages should be used at all times and in the order presented. In addition, DRM is presumably not supposed to be a linear process, but instead may require many iteration phases. DRM represents seven main types of research to be chosen from (see figure 2.4), which are applicable for different cases. Motives for choosing a type of research may vary dependent on a number of factors such as lack of understanding of existing situation or lack of understanding of success criteria. (Blessing & Chakrabarti 2009.)

2.3. Chosen type of research method in the thesis

This thesis applies the DRM to a limited extent. Given this model is tailored to comprehensive research projects such as Doctoral theses; a thorough use of DRM is neither relevant nor reasonable. This thesis will use research type 2 listed above, consisting of a comprehensive study of an existing situation since this research is undertaken when the literature does not provide links between factors of interest and selected success factors. (Blessing & Chakrabarti 2009.)

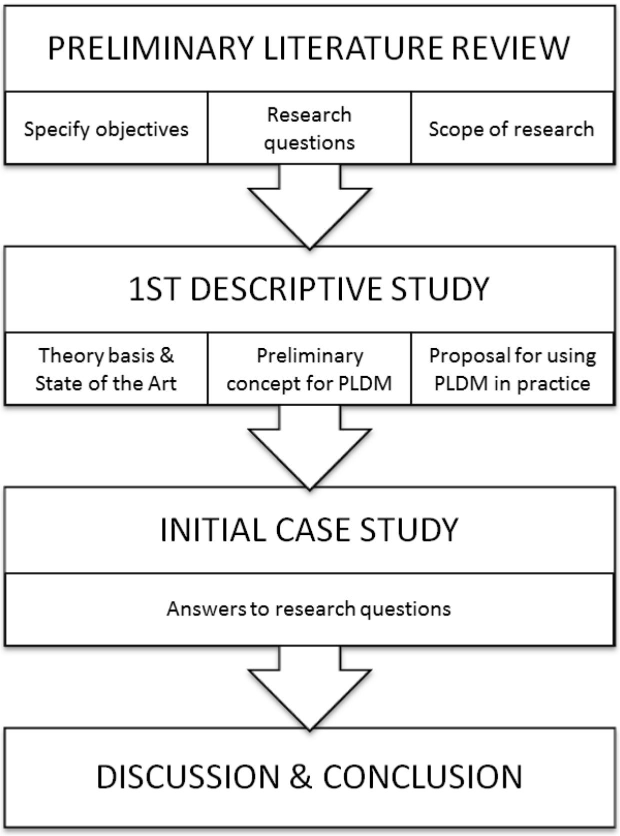


Figure 2.5. *Research process in this thesis.*

As shown in figure 2.5, this thesis starts with a preliminary literature review to clarify the direction and scope of the research in order to refine the research questions. The next stage is the first descriptive study in which the preliminary concept for the conceptual model is structured, based on the relevant theories and the state of the art. After this, a case study is conducted which aims to answer the primary objective of the thesis. Also the preliminary conceptual model is developed from the experience of the case study. Finally, the results answer the research questions.

2.4. Formulation of research questions

The final research questions are structured during the research clarification stage. During this stage initial questions that guide the review process are modified to answer the objectives more accurately.

At the beginning of the thesis project the preliminary questions focused on identifying the product's properties and life-cycle phase properties however, further research indicated that these questions were irrelevant to the model structuring. The definition for properties was still very broad at the beginning of the research and was refined as the relevant theories became apparent. It was also realised in the initial phase of concept development that the point of interest is identifying and understanding all the influencing elements in the model and the modelling process.

As research continued and the final objectives were refined it was identified that it would be suitable to divide the questions. Questions 1 and 2 address the first objective to structure a concept for the explanatory model, whereas question 3 addresses the second objective, to demonstrate and conclude results of explanatory with a case study.

2.5. Selection of relevant scientific theories and state of the art

The primary purpose for this research is to address a need within the Finnish manufacturing industry and contribute to the Design Science sector's development of related models and applications in IPPD. This research continues from work already done in the IPPD research group at TUT and employs available theories and practices from Design Science. Systems Thinking was also used to complete the theory basis to bring a holistic system level approach to this research.

One of the research objectives is to provide a conceptual model to be used in future practical applications to ease and facilitate the decision making process in product design and development. Recent work done in modelling product life-cycles is therefore seen as a core starting point to develop and refine the model.

The Flow model was chosen as a suitable method of distilling and interpreting information having proved its functionality in previous projects done by the IPPD research group. The Flow model was used to generate ready applications in product life-cycle modelling, and this valuable experience led to the decision to use it in the development of the explanatory model.

Product Configuration and Modularity was chosen purely to support the findings of the case study. This is a strong and well known area among the IPPD research group. The case study provides an opportunity to model situations that are well known to the research group, but have not yet been clearly illustrated for bigger audience.

2.6. Literature review

The literature review started from the theory basis and the state of the art in the field of Design Science. The review was conducted using a selection of keywords and terms relating to the study. Literature review covered journal databases, conference proceedings, books and doctoral dissertations from the area of Design Science, as well as a comprehensive study of the past work done in the research group at TUT.

Design Science including Theory of Technical Systems, Design Process Theory, Theory of Domains, Product Structuring, Theory of Disposition, and Property-Driven Development were already well known areas in the IPPD research group and were a good starting point for the review. The keywords and terms used to explore databases and conference proceedings were Systems Thinking, product life-cycle, product life-cycle modelling, product structure, product modularity and product configuration.

2.7. Research results

In the initial phase of this research project the final result in the preliminary objective was to integrate the explanatory model into design structure matrix based software, Dimo, which is used as a support tool in product design and development. However, the scope of this work was far larger than could be accomplished in this Master of Science thesis. For this reason, the objective was changed to provide a conceptual proposal for the explaining model and further develop the idea with a case study of partly configurable products within the manufacturing industry.

Results are given as direct responses to the research questions. Thus the source of the results is solely from the given theory basis and the state of the art and aims to provide a complete concept for the model.

2.8. Discussion and conclusion

The discussion will measure the significance of the research in the field of Design Science and will also address validity and possibilities of the research. Recommendations for further research are derived from the results of and are presented within the discussion. The conclusion chapter will mainly address the research results and the case study. The main purpose of these conclusions is to summarise the core results of the research.

3. THEORETICAL BACKGROUND

In this chapter the theory basis is presented. The order of the presented theories also represents the author's interpretation of their significance to the thesis.

In the following, seven theories are represented including Systems Thinking, Theory of Technical Systems, Theory of Design Process, Theory of Domains, Product Structuring, Theory of Dispositions and Property-Driven Development. Finally the most important elements in this thesis are summarised at the end of the chapter.

3.1. Systems Thinking

In general, Systems Thinking is the consideration of the whole system and its context (Lamb & Rhodes 2009). According to Davidz (2006), Systems Thinking regarding engineering focuses on the use of experience and tools to analyse the technical and social components and interrelationships of a system (see Lamb & Rhodes 2009).

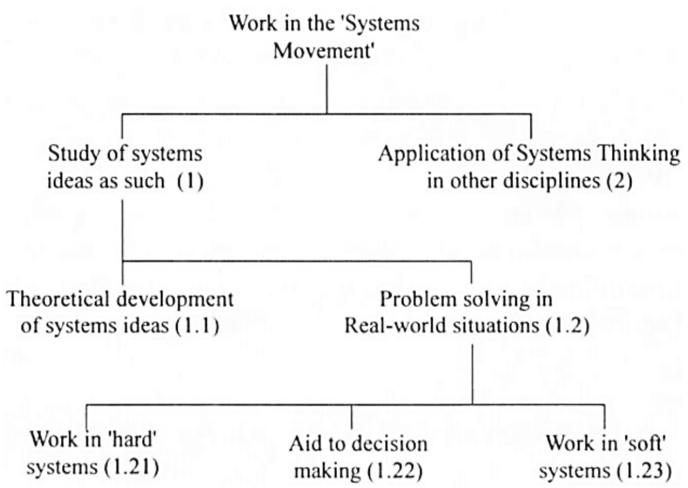


Figure 3.1. *Systems movement* (Checkland 1981).

According to Checkland & Haynes (1994), Systems Thinking evolved from organismic biologists. One of them, Ludwid von Bertalanffy argued that the ideas biologists had developed could also be applied in other systems. Bertalanffy became one of the significant influencers of the early General Systems Theory (GST), which was the influential theory behind the more recent Systems Thinking movement (see figure 3.1). The basic aim of GST and its founders, the General Systems Society was to achieve cross-disciplinary application by employing the isomorphic model. (Checkland & Haynes 1994.)

The Systems Thinking movement started from the study of systems ideas and, as such, evolved to problem solving in real world situations before moving on to research of “Hard” and “Soft” systems. “Hard” systems is represented by computer systems analysis and Systems Engineering (SE), whereas “soft” systems is represented by soft systems methodology (SSM). (Checkland & Haynes 1994.)

The division of ‘Hard’ Systems Thinking (HST) and ‘Soft’ Systems Thinking (SST) is relevant to this thesis and it also represents the most recent movement in the area of Systems Thinking. Therefore, more attention is taken into these two approaches and their differences in the next chapter.

3.1.1. Hard Systems Thinking, Soft Systems Thinking and Soft Systems Management

HST has been a popular approach since the 1950s and 1960s. According to Checkland & Haynes, hard Systems Thinking is based on goal seeking and assumes that the problematic system can be named unambiguously and its objectives can be defined precisely, allowing it to be engineered to achieve objectives. This also implies that any human activity could be regarded as a goal-seeking system (Checkland 1985). This approach is also one of the core hypotheses of SE.

Systems Engineering was developed in 1960s and has played an important role in dealing with the complex problems of engineering and technology in the field of contemporary management science. SE has been an effective approach for dealing with technological and social components of problems. However, as a quantified element, social aspects in SE are traditionally resources and do not take into account the complex nature of real human activity systems. To this dilemma SST and later SSM were developed. (Lamb & Rhodes 2009)

The ‘hard’ systems thinking of the 1950s and 1960s	The ‘soft’ systems thinking for the 1980s and 1990s?
Oriented to goal seeking	Oriented to learning
Assumes the world contains systems which can be ‘engineered’	Assumes that the world is problematical but can be explored by using system models
Assumes system models to be models of the world (ontologies)	Assumes system models to be intellectual constructs (epistemologies)
Talks the language of ‘problems’ and ‘solutions’	Talks the language of ‘issues’ and ‘accommodations’
ADVANTAGES	ADVANTAGES
Allows the use of powerful techniques	Is available to both problem owners and professional practitioners; keeps in touch with the human content of problem situations
DISADVANTAGES	DISADVANTAGES
May need professional practitioners	Does not produce final answers
May lose touch with aspects beyond the logic of the problem situation	Accepts that inquiry is never-ending

Figure 3.2. *Description of “hard” systems and “soft” systems.* (Checkland 1985).

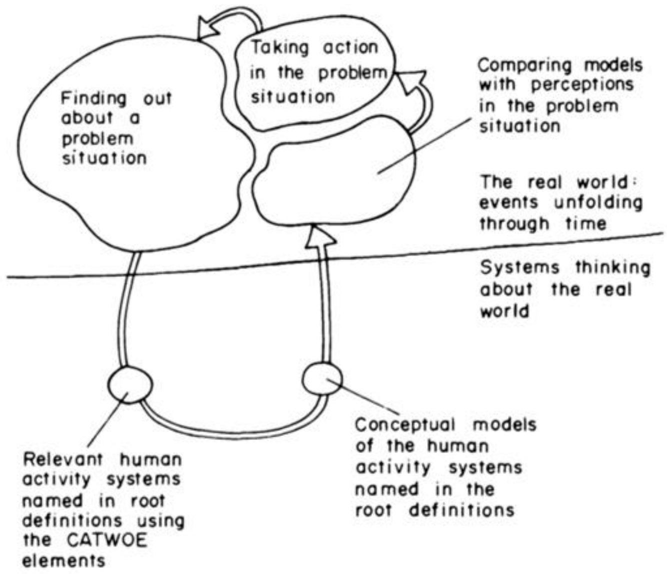
SST is the more recent approach and has been developing since the 1980s and 1990s. It does not assume that the complexity of human activities can be captured in systemic models. Instead it aims toward learning rather than to optimisation or satisfaction. In addition, SST concentrates on issues and ‘accommodations’ rather than on solutions. (Checkland 1985.) The comparison between HST and SST is shown in figure 3.2.

From SST emerged SSM, to which Peter Checkland has been an essential contributor. SSM was a result of research into the possibilities of SE under problematic management situations. (Checkland & Haynes 1994.) It was quickly discovered that SE was not applicable for these kinds of human activity systems, where conflicting viewpoints and interests are open for frequent change and where a consensus of clear objectives could not be clearly specified. (Checkland & Haynes 1994; Checkland 1985.)

Before going into SSM in more detail, the Checkland’s summary of Systems Thinking is presented. This summary has been influential for the development of SSM. It comprises the following seven points:

- In Systems Thinking whole entities are substantial. This way all the properties can be depicted as a single whole, which in terms of the parts of the whole would not have a meaning.
- Systems Thinking is setting abstract wholes against the discovered real world in order to enable learning.
- In Systems Thinking HST and SST exist as complementary approaches.
- SSM is a systemic process of enquiry using system models. It also consists of the HST approach.
- Systems Thinking should use the name of ‘holon’ for the constructed abstract entities instead of ‘system’ to avoid confusions. The word, ‘system’ is common in everyday language and has many interpretations, therefore ‘holon’ could represent a more accurate technical term.
- SSM uses a specific kind of holon, that is human activity system. This is a set of activities which construct a purposeful whole.
- In SSM it is necessary to create several competing models of human activity systems and, by doing so, learn their relevance to real life.

(Checkland & Scholes 1990, cited in Zexian & Xuhui 2010.)



CATWOE:

C (‘*customers*’)	*Who would be victims or beneficiaries of this system were it to exist?*
A (‘*actors*’)	*Who would carry out the activities of this system?*
T (‘*transformation process*’)	*What input is transformed into what output by this system?*
W (‘*Weltanschauung*’)	*What image of the world makes this system meaningful?*
O (‘*owner*’)	*Who could abolish this system?*
E (‘*environmental constraints*’)	*What external constraints does this system take as given?*

Figure 3.3. *The nature of soft systems methodology by Checkland. This figure also includes the elements of CATWOE* (Checkland 1985).

The nature of SSM is seen in figure 3.3 above. It is a cyclic model, which starts from finding out about a problem and carrying on organized Systems Thinking of the real world situation. Some human activity systems are carefully named in ‘root definitions’ (RDs) (Checkland 1981). RDs purpose is to explicitly name a number of features of the relevant systems using CATWOE elements, which function as a checklist to include all the relevant human activity elements in the thinking process. Mnemonic CATWOE comes from words, customers, actors, transformation process, weltanschauung (worldview), owner and environmental constraints. Figure 3.3 shows also specified questions pertaining to each of the elements. Conceptual models of the systems are structured. They are models of focused activity considered pertinent for analysing the problem situation. A debate about the situation is built by comparing models with insights of the real world situation. The aim of the debate is to find possible changes that follow two principles; systematically wanted, and culturally reasonable in the situation. After this the cycle begins again. (Checkland 1985.)

It can be said that SSM cyclic model resembles other cyclic learning models such as Kolb’s learning cycle (Kolb 1984). So, what is the contribution to the systems practice? Checkland (1985) states that the most significant factor in shifting from HST to SST is from thinking in terms of models of the world, to thinking in models relevant to arguing about the world. Furthermore, as Checkland highlights SST is somewhat an extension of HST to better manage the human activity systems.

In this thesis, Checkland's interpretation of Systems Thinking is used as a starting point. As the cases of product life-cycle disposition model can be problematically complex and deal strongly with human activity systems, SSM becomes relevant.

3.1.2. Distinctive Systems Thinking Skills

Contrary to Checkland's approach, Richmond (1993) states there are seven distinctive Systems Thinking skills. See figure 3.4. These skills include dynamic Systems Thinking, closed-loop thinking, generic thinking, structural thinking, operational thinking, continuum thinking, and scientific thinking. This kind of distinction is especially good for teaching purposes, when in practise many of these skills work simultaneously.

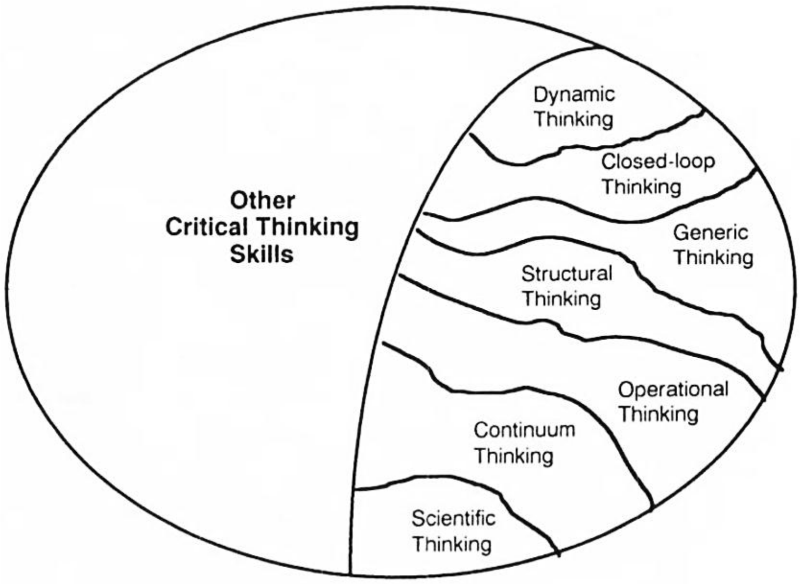


Figure 3.4. *Critical thinking skills in Systems Thinking* (Richmond 1993).

To describe these distinctions in more detail, it is natural to start from dynamics thinking. This type of Systems Thinking, from a skill point of view, is the ability to see and conclude behaviour patterns of phenomena. Dynamic patterns of behaviour are often seen as a part of closed-loop processes and are subject to change over time. An example of this is a carrot harvesting pipeline in figure 3.5. (Richmond 1993.)

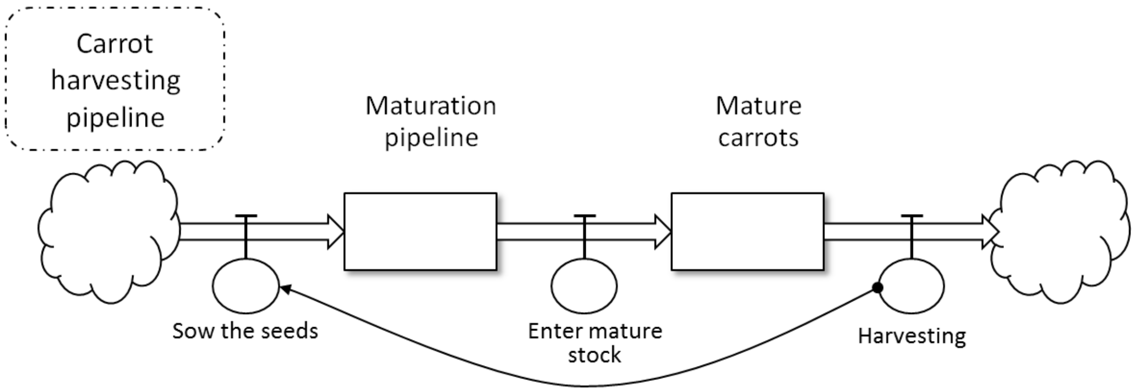


Figure 3.5. *Carrot maturation pipeline dynamic structure* (altered from Richmond 1993).

Closed-loop thinking goes hand in hand with dynamic Systems Thinking and moves it forward. It is the ability to see systems as interdependent processes. The example in figure 3.5 can be interpreted as an example of a closed-loop system, but the emphasis is on the loops themselves i.e. circular cause and effect relationships. The core of this thinking is identifying that the loops can be causes of the behaviour in the patterns rather than other external forces. Instead, the external sources can be effected by the circular cause and effect pattern. (Richmond 1993.)

Generic thinking approaches a target from a general, holistic point of view, rather than concentrating on specifics. Richmond uses the example of Gorbachev, the leader of former Soviet Union in 1980s. If thinking specifically, it can be construed that Gorbachev was responsible for bringing freedom to the country. But from a general perspective it can be claimed that external global circumstances strived for freedom and Gorbachev was only a one small instrument in the puzzle. (Richmond 1993.)

Structural thinking is, according to Richmond, the most disciplined of the Systems Thinking approaches. For this thinking units of measure and dimensions are important and the focus is specifically in the distinction and follow-up of stock and flow. Figure 3.6 represents an example of this system. In this figure, there are two distinctive flows marked structurally in correct manner. This kind of division emphasizes the importance of being able to measure physical quantities such as the amount of liquid in litres and the number of bottles apiece. In proportion, a dynamic causal-loop diagram might not be applicable in structural thinking, because dynamic thinking does not follow the principles of structural thinking. (Richmond 1993.)

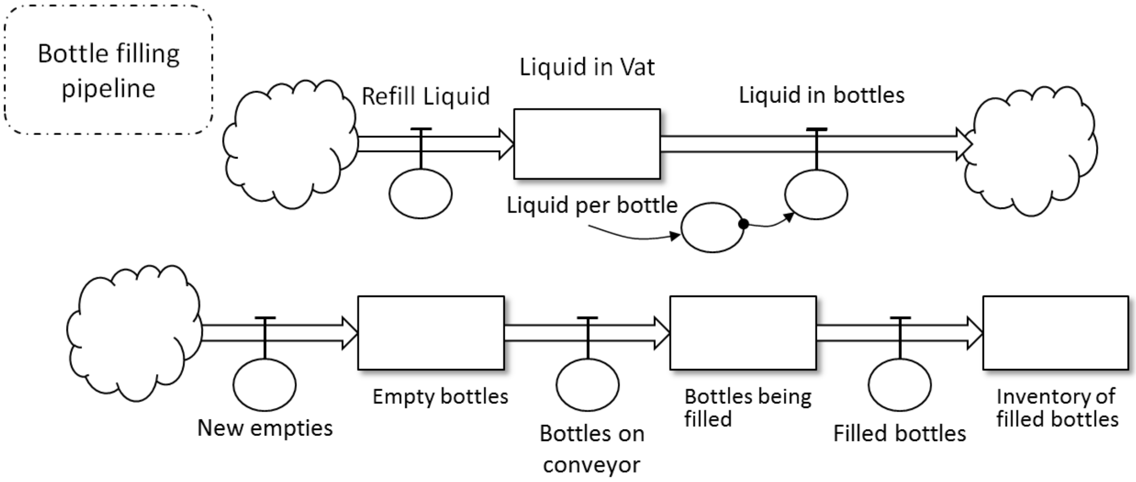


Figure 3.6. *Structural diagram of liquid and fillable bottles* (altered from Richmond 1993).

The next skill is operational thinking, which goes hand in hand with structural thinking. It has the same principles as structural thinking, but additionally focuses on thinking in terms of how things really work rather than mapping the theoretical function. The operational thinking skill is identifying a realistic process of a system. From an operational point of view this kind of process enables concentration on the factors that are the real levers of the process. (Richmond 1993.)

The next type of Systems Thinking is continuum thinking, based on a continuous modelling approach. Richmond states that continuum thinking is closely related to generic thinking. This is because both emphasize the ability to see connections and interrelationships instead of sharp boundaries and disconnections. As an example, Richmond uses water consumption process. In a discrete model this could be the following: Water consumption is normal when available water level is above zero, if not it is zero. The continuous version of this same case would follow an operational specification, that is, water consumption = population X Water per person. Water per person in this case is a continuous flow of available water. (Richmond 1993.)

Finally, Richmond (1993) identifies scientific Systems Thinking. This form of Systems Thinking emphasizes quantification which in this case means that non-measurable factors, such as self-confidence that can be quantified for example scaling it from 0-100. Zero would indicate zero self-confidence and a hundred the maximum possible amount. From this kind of scaling more rigorous analysis can be made. Additionally, scientific thinking requires precision in testing hypotheses. In scientific thinking it is the ability to modify only one thing at a time and hold all else unchanged.

3.2. Design Science

Design Science (DS), according to Hubka & Eder (1996) is "a system of logically related knowledge, which should contain and organise the complete knowledge about and for designing". The four areas of knowledge are illustrated in figure 3.7. DS originates primarily from the German-speaking world. The original field of application was machine design resulting in engineering works and mechanical design playing a significant role in the early phases of Design Science's development. However, in recent times, systematics and methodologies developed under the design science are used more broadly among product design and development. (Lehtonen 2007.)

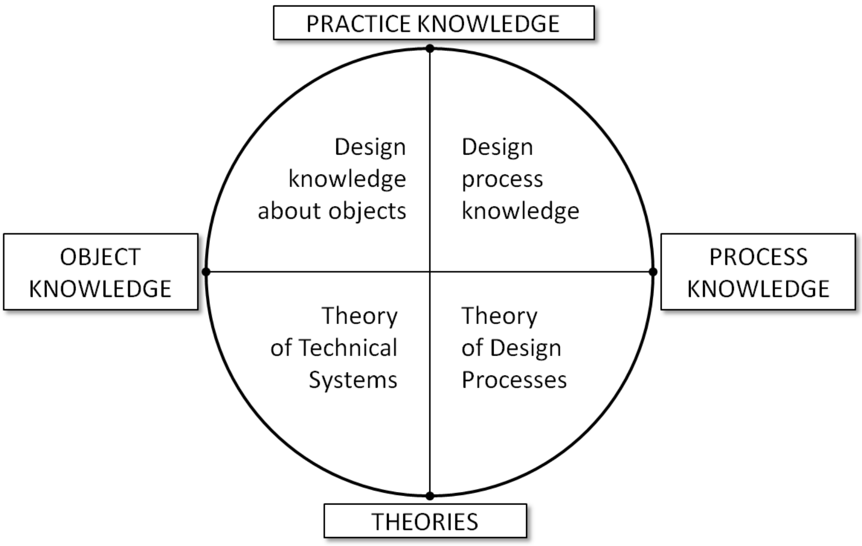


Figure 3.7. *Main areas of knowledge and categories in Design Science* (altered from Hubka & Eder 1996).

According to the knowledge of the IPPD research group, Design Science originates from the research of Vladimir Hubka & Ernst Eder. Mogens Myrup Andreasen followed Hubka with his Theory of Domains and Olesen's Disposition theory succeeded Andreasen's work in the area of dispositional mechanisms. Christian Weber also follows the early Design Science of Hubka with additional influence from Nam Pao Suh's research on Axiomatic Design.

The following section introduces six influential theory bases of design science. These are Theory of Technical Systems, Theory of Design Process, Theory of Domains, Product Structuring, Theory of Dispositions and Property-Driven Development.

3.2.1. Theory of Technical Systems

Theory of Technical Systems (TTS) was introduced by Vladimir Hubka and Ernst Eder. The aim of TTS is to present a comprehensive theory capable of explaining the intrinsic nature of any technical system. The theory is based on a transformation system, seen in figure 3.8. Hubka & Eder state that a technical system is the process of achieving a desired outcome through a series of intermediate states. (Hubka & Eder 1988.)

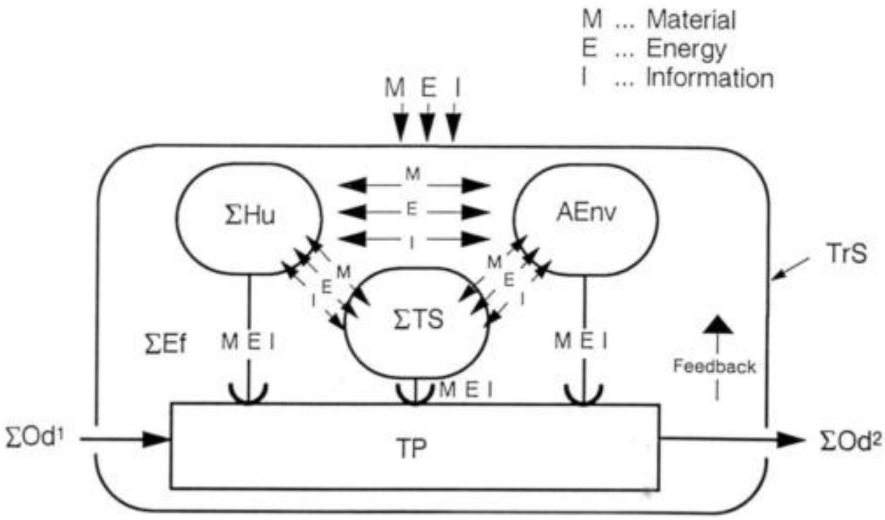


Figure 3.8. *Transformation system of the Theory of Technical Systems* (Hubka & Eder 1988).

According to Hubka & Eder, as a starting point, the theory requires needs and demands. This makes the assumption that any technical system exists to fulfil a need. In the figure below ΣOd^1 represents the original state, whereas ΣOd^2 is the final, desired state founded on the need. The operation is called a technical process (TP). The other elements which cause the transformation are effects (ΣEf) and include the sum of technical system (ΣTS), the sum of human system (ΣHu) and the active environment (AEnv). The flows between these three systems are material, energy and information. (Hubka & Eder 1988.)

Hubka & Eder (1988) identify the three most influential advantages of this approach:

- It enables transfer of technical experience between different areas of technical systems.
- It enables working methods to develop for engineers independent of the product type which can be transferred between different fields of industries.
- It enables problems to be seen as part of the whole by the incorporating Systems Thinking.

The theory of technical systems works on multiple levels of abstraction. Hubka & Eder state there is always a causal relationship between the aims and the means that empower them. This approach can be shown as an aims-means- tree -graph in figure 3.9. It shows how the main function, Ef, of the technical system is divided into sub-functions. (Hubka & Eder 1988.) As the tree goes on, the technical system transfers from the product’s overall function to the effects of indivisible elements (see Lehtonen 2007).

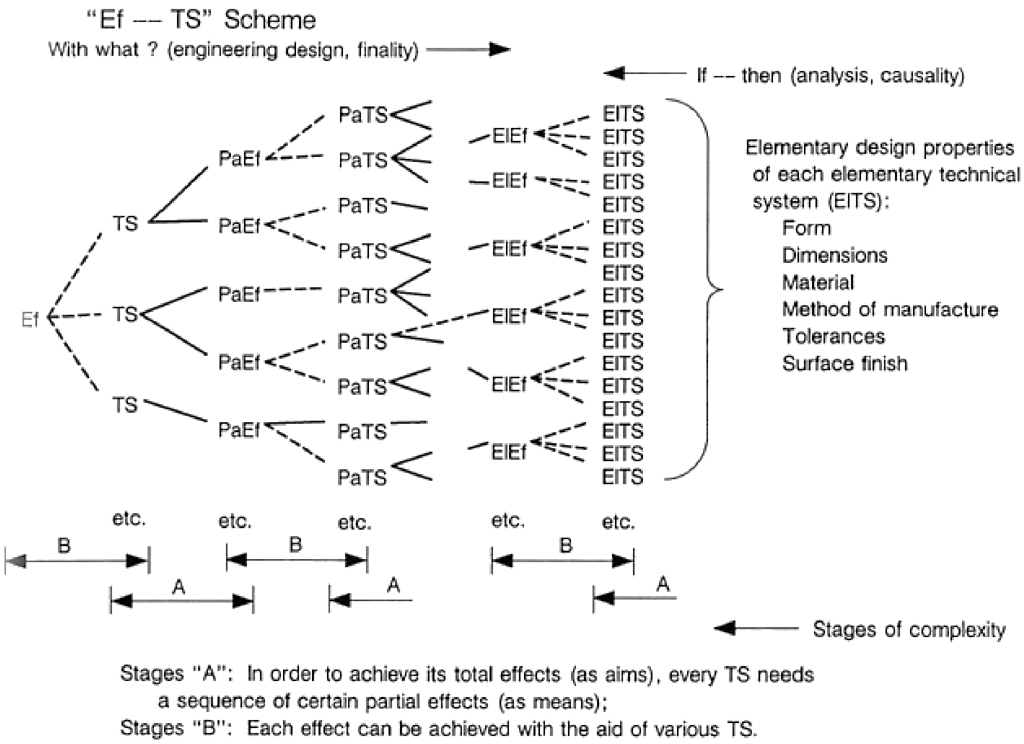


Figure 3.9. *Aims-means- tree -graph* (Hubka & Eder 1988).

The relevance to this thesis comes from the fact that transformation is done by the design process. The aims-means- tree with all its levels can be seen as different phases of design (Lehtonen 2007). Also the levels can represent the influence of different people involved in the whole production process, from abstraction to detailing. Furthermore, as Olesen describes, the Theory of Technical System enables the linking of design characteristics between the phases of development and production system (Olesen 1992).

3.2.2. Theory of Design Process

The natural successor to the Theory of Technical Systems is the theory of Design Process, which is based on a similar philosophy to the TTS (Juuti 2008). Design Process is all about designing a transformation process, which includes designers, working methods, design information, design management, active environment and operands. Operands are, as in TTS, original states that consist of needs, requirements and constraints of the technical system. The final state is a full information description for possible manufacture. (Hubka & Eder 1988.)

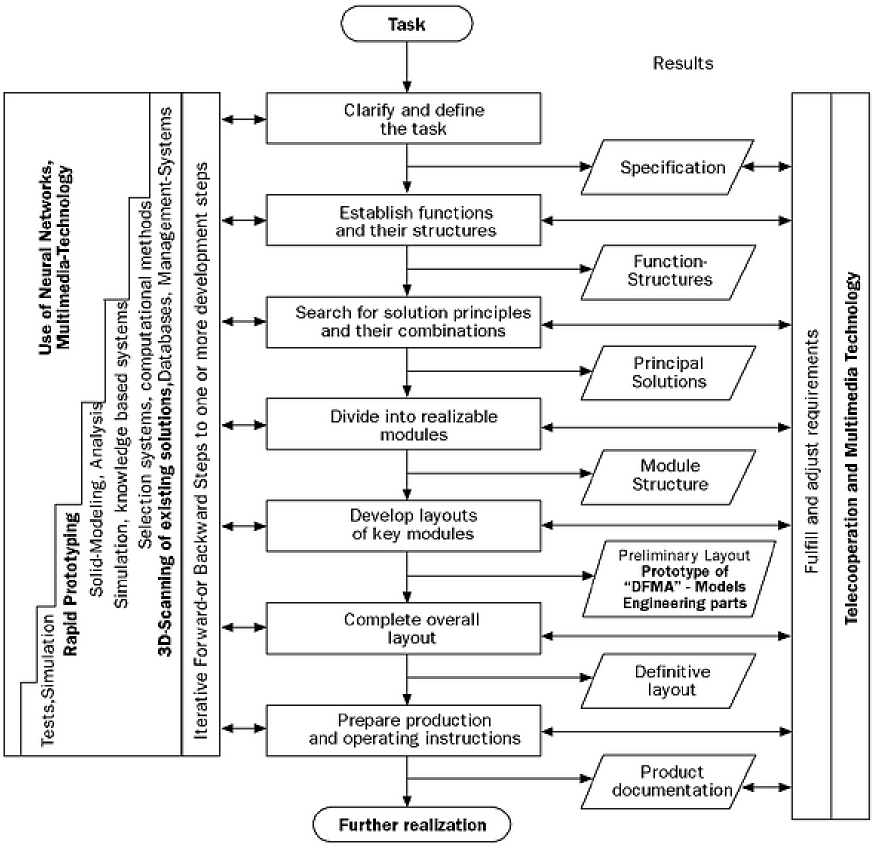


Figure 3.10. *The Systematical Design Process VDI 2221 standard* (Grote et al. 1998).

Currently there exist several different design processes that follow the same idea as Hubka & Eder's Design Process and develop products from abstraction level to detail solutions. Systematic design processes have taken the theory of Design Process and included more detail. Systematic design processes have been developed, above all, for general education purposes. Popular design processes, such as Verein der Deutschen Ingenieurs VDI 2221 (figure 3.10) and Konstruktionslehre by Gerhard Pahl and Wolfgang Beitz, represent typical approaches that have been developed based on the experiences of their developers in practical design work. (Lehtonen 2007.)

3.2.3. Theory of Domains

The Theory of Domains, defined by Mogens Myrup Andreasen, is a synthesised theory of product development, continuing Hubka & Eder's TTS to achieve a more practical approach (Lehtonen 2007). In the theory, the product synthesis is divided into four domains; process system, effect system, organ system and part system. The domains represent different functional areas in a company involved in product development. Figure 3.11 shows how the design process evolves from abstraction to actuality as more detail is presented within each domain and from one domain to another. (Andreasen 1980.)

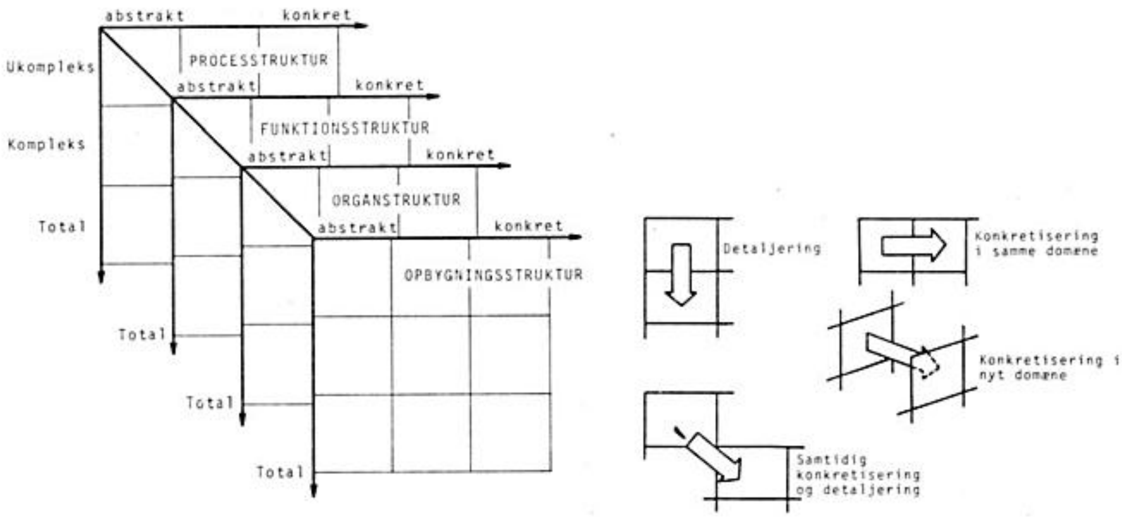


Figure 3.11. *Theory of domains, the progression from abstract level into more concrete, and more detail in each domain, and from domain to another* (Andreasen 1980).

Domains can be seen as different phases of the design process, leading abstract ideas of a transformation process into detailed part design. Process system is the transformation process occurring when using a product. Here, the transformations should reflect the needs and demands of a product. Function system represents the effects required to realise the desired transformations. (Andreasen et al. 1997, cited in Juuti 2008.) The organ system behaves as a function carrier, structuring the functions into distinct areas (see Juuti 2008). Part system is the most concrete domain level, where the parts of a product are realised (Andreasen et al. 1997, cited in Juuti 2008).

According to Lehtonen (2007), domain theory provides the basis for dispositional mechanics. Olesen adds that a product’s properties are synthesised into a product consisting of all four domains. This enables us to represent each of the domains by a series of design characteristics. Furthermore, Olesen suggests a production system can be identified as having similar set of levels as the theory of domain. (Olesen 1992.) For this thesis, the Theory of Domains provides a precedent for the depiction of interrelationships throughout design and production systems.

3.2.4. Product Structuring

The Product Structuring approach comprehensively continues from Andreasen’s Domain Theory. This chapter provides a short overview.

Product structure is the description of the interrelationships between product elements in a system model to create structure, based on a chosen point of view. A system model consists of elements and their relationships.

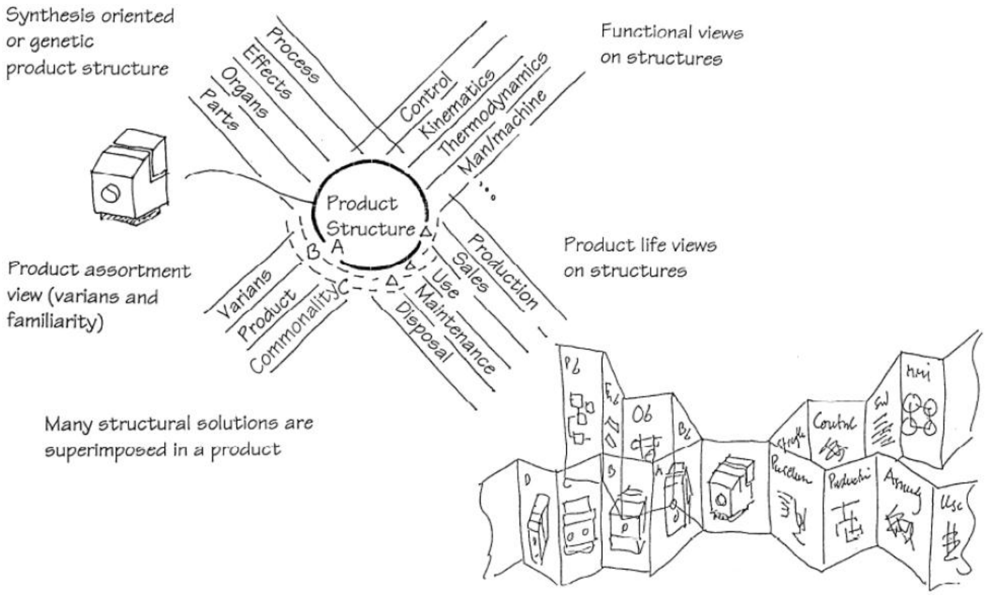


Figure 3.12. *Different point of views in product structure* (Andreasen et al. 1997).

As presented in figure 3.12, Andreasen et al. (1996) describes four different point of views from which to realise product structuring, including: Generic, functional, life-cycle-oriented and product assortment.

Product architecture is often confused with product structure and, in some cases, the term is used as interchangeably (Huhtala & Pulkkinen 2009). Product architecture plays a key role in product structure and can be seen as the description of product assortment, one of the viewpoints of product structuring (Juuti 2008).

The significance of product structuring to this thesis comes from the statement that behaviour and function of a product depend on its structure (Andreasen et al. 1996). Another important aspect for this thesis is the connection of product structure to product's life-cycle.

3.2.5. Theory of Dispositions

Olesen (1992) introduces Theory of Dispositions, which is originally designed to help concurrent development, especially between product development and production development. In his research, Olesen ran into a problem whereby the product development theories, methodologies or tools of that time did not take other functional areas into consideration other than those specifically being focussed on. Other functional areas were often only taken into account during the formulation of tasks and targets. (Olesen 1992). By functional area, Olesen (1992) means the part of the organisation that is responsible for activities in a particular area of production.

A typical example of this problem is the VDI 2221 norm, which is a common product design and development methodology. It specifies a general procedure for the development of products, from defining the tasks to the final product documentation. This procedure takes all the other functional areas as given and only considers them when the tasks and specifications are named in the product development process. So the resulting idea is that a particular decision in product development obliges us to accept a particular choice in production system. In VDI 2221, it is up to the product developer in the specific situation to evaluate the extent to which the production system ought or must be taken into consideration during product development. Other common frameworks of methodologies also ignore the same problem of concurrent development (Olesen 1992.)

Olesen (1992) states that the concurrent development, or simultaneous engineering, is the new paradigm, a direction to where companies should be aiming. Foremann (1989) defines this simultaneous engineering as the integrated concurrent design of products and their associated manufacturing processes (see Olesen 1992). Furthermore Integrated Product Development is a framework found by Andreasen & Hein (1987), which also contributes to the same scheme by integrating sales, product design and production systems into one coherent system (see figure 3.13 below).

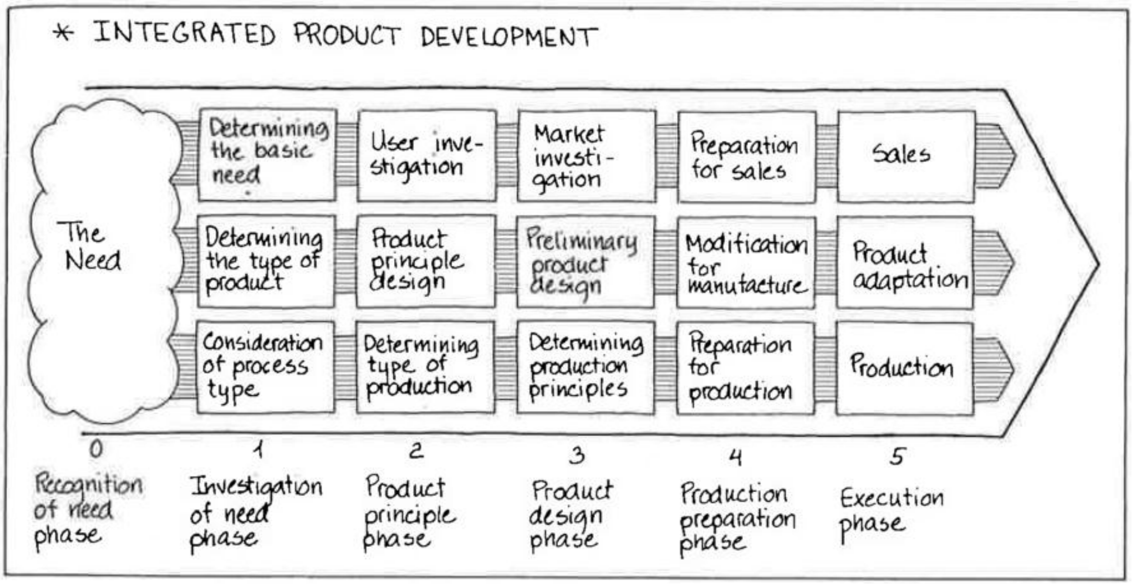


Figure 3.13. *Integrated product development* (Andreasen & Hein 1987).

Olesen claims there is a need for tools which can deal with this parallelism, concurrently taking into account other processes along with the traditional product development process. This is based on the situation in 1990s, where available tools addressed only very specific areas of integration effects between product development and production process. (Olesen 1992.) A number of tools and methods now exist to manage this process, in particular matrix-based computer software whereby the dependencies of different elements in the concurrent development process are analysed. Quality Function Deployment (QFD) is one example of the methods, where the integration of product and production techniques has been successful.

To this need of concurrent development tool Olesen (1992) provides a Theory of Dispositions, which is a conceptual apparatus to depict relationships/effects between elements or tasks from different functional areas. This is based on the hypothesis that it is possible to explicitly describe the parameter relationships and the effects which they enable control over. Olesen (1992) claims that this is more holistic approach in depicting parameter relationships in product and production systems. Dispositions are decisions taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas (Olesen 1992). In figure 3.14, a generic model of dispositions is shown, where two activities, A and B, from different functional areas affect each other. The decision consists of two parts; data, and disposition. The data part is a description of the task, whereas the dispositional part is the description of change in the activity caused by a decision in other activity.

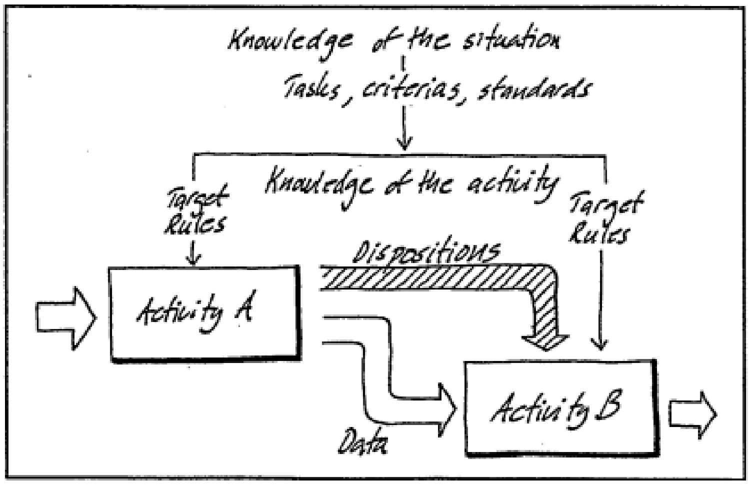


Figure 3.14. *Generic model of dispositions* (Olesen 1992).

According to Olesen (1992), dispositions are not just seen in terms of two activities, but in sequence phenomena in production. Frick (1991) defines this kind of activity chains as “a continuous chain of activities which perform a principal task for the company” (see Olesen 1992). Thereby, a generic model of dispositions is valid for all the activities in such a chain. A complete picture of the design dispositions related to product and production are obtained by combining all the design activities with all the activities involved in the development and operation of the production system.

The true value of dispositions is derived from conscious decisions. Since the disposition carries a set of parameters from one functional area to another, the data part in an activity, as defined earlier, forms the input for other activities. In this case, the true parameter relationships can reflect the intended process. So with this kind of system, the effects of the decisions can be compared to the desired outcomes. It all comes down to conscious decisions - a developer must take into account other dispositions in other functional areas rather than only the one the developer might be specifically interested in. Furthermore, managing dispositions does not necessarily mean trying to avoid or decrease them, but attempting to control them in order to meet the overall targets. Consciousness comes from the fact that dispositions are subject to natural laws. They appear whether one is aware of them or not. (Olesen 1992.)

For this thesis the most significant part of Olesen's Theory of Dispositions is the total development model. The total development model takes product's whole life cycle into consideration so dispositions can be seen beyond just the product development and production's functional areas. (Olesen 1992.) Olesen divides product life-cycle into different stages, as illustrated in figure 3.15.

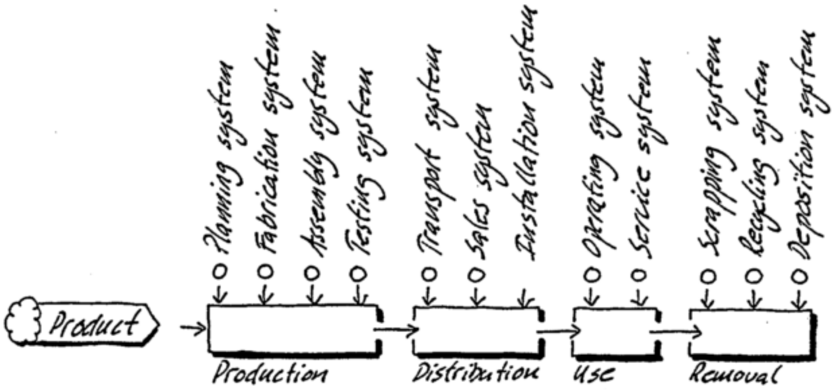


Figure 3.15. *Product life-cycle according to Olesen* (1992).

It is thus possible to define parameter relationships from development of product through production oriented systems until the very end of product's life cycle. In addition, Olesen (1992) provides a score model for the product development and for product life cycle. This model shows the large number of areas in which dispositions will have effects in a development situation (Olesen 1992).

In the life cycle model, dispositions are measured in terms of their effects on universal virtues during product development. Universal virtues are general, measurable quantities which can be traced during different life cycle phases. The virtues are the following:

- Costs
- Throughput time
- Quality
- Efficiency
- Flexibility
- Risk
- Environment

(Olesen 1992)

Other parameters can also be measured, but Olesen (1992) uses these universal virtues to reflect the dispositional behaviour of activities. In a typical situation, attention will be focused on few of these virtues. In this kind of product life cycle, disposition modelling aims to estimate the results of decisions at an early stage of product development. (Olesen 1992.)

Finally we get to Olesen's (1992) dispositional mechanism, which is a more detailed application of how to use dispositional thinking in practice (see figure 3.16). According to Olesen (1992) the dispositional mechanism consists of:

- Two development activities from different functional areas, where one of the following are to be determined: concept, structure or details
- Data connection and dispositional connection between activities
- Objectives for both activities
- Rules for how the decisions can achieve the objectives
- Possible choices of design characteristics
- Calculation of the dispositional effects of particular design choices

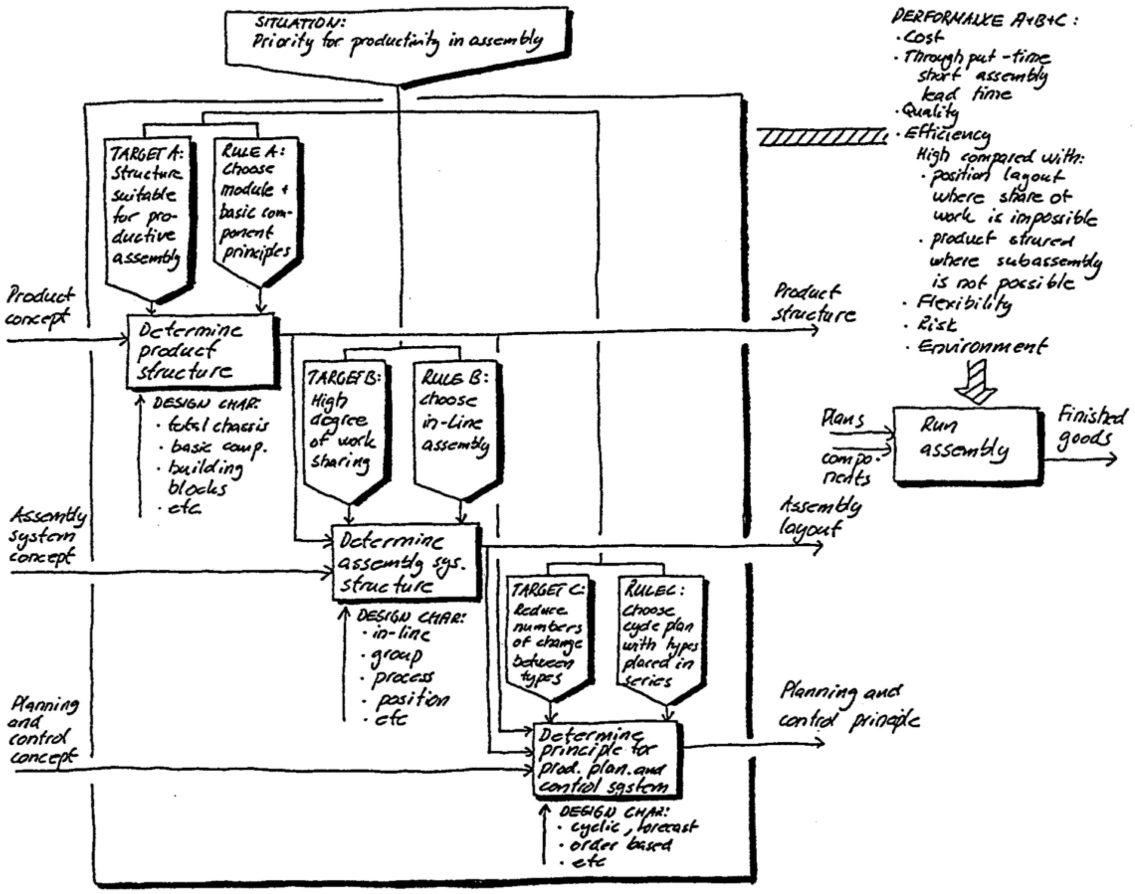


Figure 3.16. *Generic model of dispositions* (Olesen 1992).

With the dispositional mechanism as a basic pattern, it is possible to depict real cases of dispositional effects in detail. Thus, it is possible to isolate specific design characteristics that are the source for dispositional effects. However, at this point it is important to clarify Olesen's meaning of the term design characteristic, as it is not consistent with the artefact characteristics presented and used later in this thesis. Olesen's meaning refers simply to the nature of a design activity.

3.2.6. Property-Driven Development

Characteristics-Properties Modelling / Property-Driven Development (CPM/PDD) was founded by Christian Weber in the 1990's. It consists of CPM, which contributes to product modelling, and PDD, which explains process phenomena in product design & development (Weber 2012).

CPM/PDD is based on a division between product characteristics and properties; two different concepts for describing products and their behaviour (Weber 2012). Similar product distinctions between characteristics and properties have been used in Design Theory and Methodology for a long time, but with different terminology. For example, Hubka & Eder (1996), define internal properties are equivalent to Weber's product characteristics, whilst external properties are equivalent to Weber's product properties. In figure 3.17 is represented more detail descriptions of Hubka & Eder's internal and external properties.

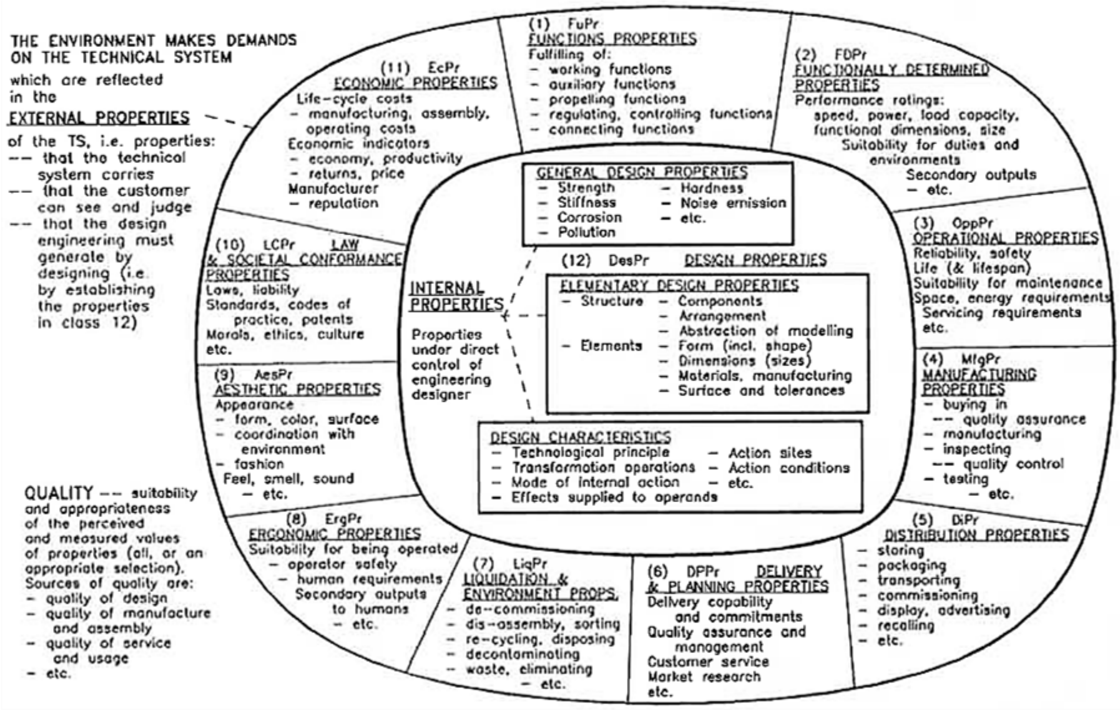


Figure 3.17. *Description of internal and external product properties.* (Hubka & Eder 1996)

Also, more research can be found dealing with the same subject. Other terms used for characteristics and properties include design parameters and functional parameters (Suh 1990), and independent and dependent properties (Birkhofer & Wäldele 2009). However, Andreasen (1980) uses the terms characteristics and properties, but with directly opposite meanings (see Weber 2012).

Characteristics are made up of a structure, shape, dimensions, materials and surfaces of a product. Engineers and designers involved in product development can influence or determine characteristics of a product. (Weber 2012.)

Conversely, properties define the product's behaviour, such as weight, function, safety and reliability. Properties also describe a product's nature e.g. assemblability, testability, costs and environmental friendliness. However, properties cannot be directly influenced by developers or designers. The influence only occurs indirectly through product characteristics. (Weber 2012.)

CPM studies the relationships between characteristics and properties (Weber 2012). In CPM a third group of parameters is introduced, which is called external conditions (EC) (Weber 2012). EC describes the current or supposed environment/system around properties and characteristics – those factors beyond the influence of the product itself (Weber 2007, cited in Weber 2012). Weber describes examples of EC, such as load conditions for the property strength, user profiles for usability and life-cycle infrastructure for "environmental impacts". Further examples mentioned are maintenance infrastructures for service and repair properties, and cultural influences on aesthetic properties. X-system is yet another term that is used to describe EC. In this context, Design for X (DFX), gains a more specific definition. (Weber 2012.)

PDD sees product design and development as a process including several cycles of the following phases (figure 3.18):

1. Synthesis (R_j^{-1})
2. Analysis (R_j)
3. Determining individual deviations
4. Overall evaluation

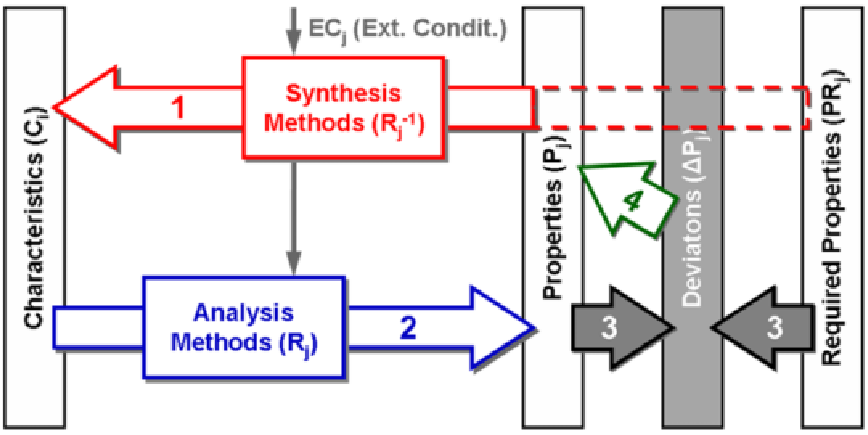


Figure 3.18. *Product development process through PDD* (Weber 2012).

The first step, synthesis, starts from required properties (PR_j) and moves toward the estimated characteristics of the future solution. In practice, this can mean starting to work from existing, previous designs or, at the very least, using some known solutions from properties (P_j). The next step, analysis, sees the properties that were used in the previous step analysed along with all other relevant properties. The third step is determining individual deviations. This means that results of the analysis are compared with the required properties. As an outcome, deviations (ΔP_j) are identified, describing the shortcomings of the current design. Finally, an overall evaluation is conducted and the main problems are extracted, as well as determinations on how to proceed further. In practice, this means choosing the properties to be addressed in the next synthesis-analysis-evaluation cycle. Figure 3.18 also depicts the external conditions (EC_j). For the phases synthesis and analysis EC_j are considered constraints. (Weber 2012.)

When proceeding from one cycle to the next, both the characteristics and the properties side of the product are expanded. For the synthesis step this means more and more established characteristics going into more detailed solutions. The analysis step more accurately predicts the behaviour of a product as the cycles continue. (Weber 2012.)

In this thesis, CPM/PDD theory builds a base for the concept of a product disposition model however, the name artefact is used instead of a product later in the thesis to overcome possible confusion. The concept applies the notion that every product has characteristics and properties, and the design process has a direct impact on the product’s characteristics, and indirectly, on properties. Furthermore, the concept for the model follows the reasoning of PDD, whereby design process is seen as a cycle of synthesis-analysis-evaluation.

3.3. Summary of the Theory Basis

This thesis has represented seven major theory bases, including Systems Thinking and Design Science, which is further divided into Theory of Technical Systems, Design Process Theory, Theory of Domains, Product Structuring, Theory of Disposition, and Property-Driven Development. The interrelationships between each of the theories are depicted in figure 3.19. The figure also illustrates them in hierarchical order with their relevant elements emphasized.

Systems thinking is seen as the blanket for the whole theory base, providing the mind-set for modelling systems and defining the possibility for interconnections between system elements. Following this, are the different theories from Design Science. The Theory of Technical Systems is where DS began, thus all the successors are based on it. In this case, the key learning from TTS is the transformation process, which always starts with requirements and ends at the final, desired state. And so, the complementary theories of Design Process and the Domain Theory are derived. They provide a framework, in which Product Development is seen as a process starting with an abstract idea and, through activities such as planning and development is transformed to more detail until a product is realised.

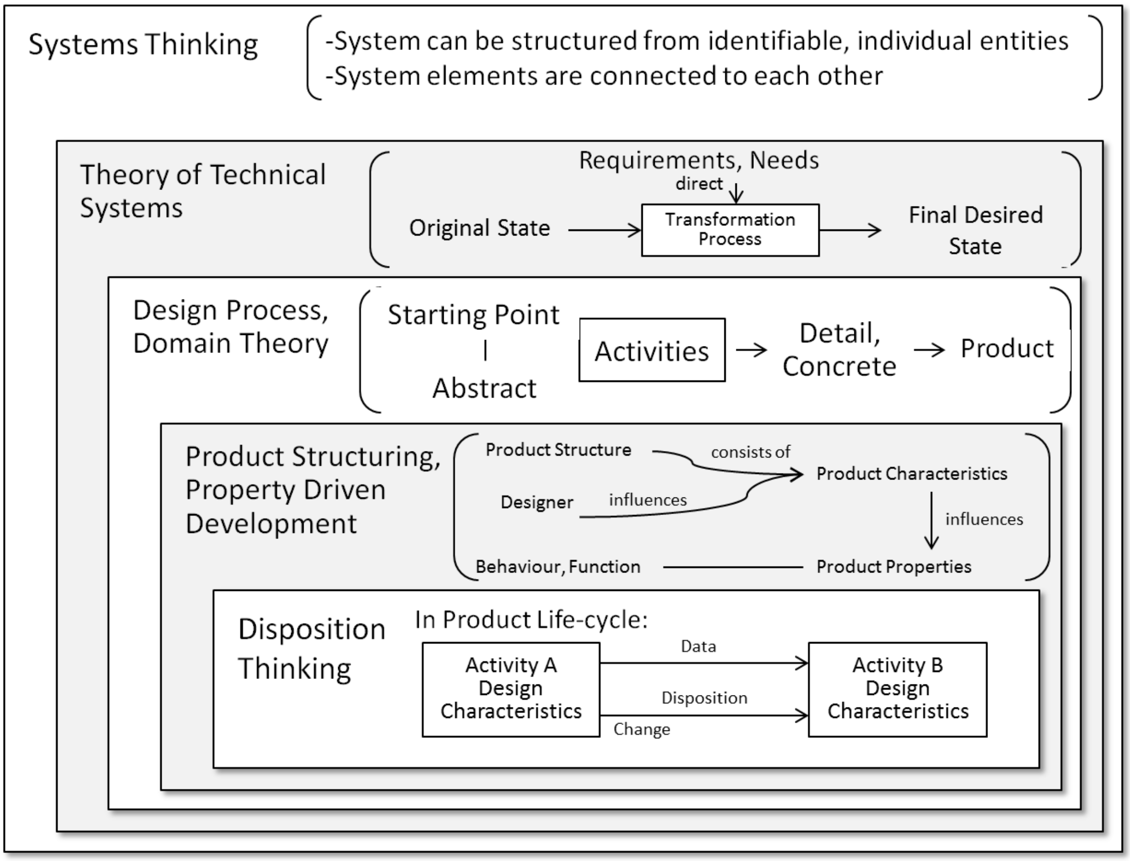


Figure 3.19. *Hierarchical order of the theory basis. In addition the relevant definitions and characteristics of each theory are summarised.*

PDD is the mind-set whereby a product can be influenced through changes to artefact characteristics and these, in turn are able to effect artefact properties. The design process in PDD works cyclically. Existing artefact properties are compared to desired properties and possible changes are directed back to changing the characteristics once again. Product structuring supports the PDD-design process through its assumption that product properties are caused by product structure.

Finally, Disposition Theory defines the existence of dispositions in product life-cycle processes, caused by changes in company's activities.

In the thesis, SSM is chosen as the framework for model development because it recognises a constant learning cycle of system understanding, where it is not presumed one problem has only one solution.

One conflict was recognised during the literature review process and further sketching the early version for the explaining model. The PDD and disposition theory does not fully complement each other, as the PDD is an artefact characteristics based-approach whereas the Disposition Theory concentrates on activity.

In this case, the Disposition Theory by Olesen is not directly applicable for the explaining model. More references to an artefact-orientated approach must be sourced from the state of the art.

4. STATE OF THE ART

In this chapter the state of the art is presented. It includes four distinctive areas including, product life-cycle modelling, complexity management approaches, flow modelling and product configuration and modularity. The first three areas have a great influence on concept development for the explanatory model whilst the final area is relevant to the case study. A summary of the most relevant observations and highlights is included at the end of this chapter.

4.1. Product life-cycle modelling

As presented in Design Science, several product design processes exist. These design processes structure product design and development into identifiable phases and inform the larger product life-cycle process.

Product life-cycle modelling is a decision making support approach for the early phases of product design and development. It is an approach for collaborative design and interdisciplinary approaches because its ability to highlight interrelationships between a product and its whole life-cycle. The broader concept is presented shortly, including approaches for product life-cycle orientation and modelling information.

At this point, it must be emphasised that this thesis does not cover the Product Life-cycle Management (PLM) environment, which is an extension of Product Data Management application. Commercial PLM is used to manage all data and work completed in a project related to a product's life-cycle and usually becomes realised in software (Gopsill et al. 2011). Pakkanen et al. (2012) states these commercially available information technology applications offer fixed data structures for storing and managing information and mainly address handling the general information of engineering bill of materials and product development versions and thus, do not address the expedience of the product elements in relation to their life-cycle requirements. Therefore PLM does not provide solutions for this study area at this point.

4.1.1. Approaches for product life-cycle orientation

Systematic design processes such as VDI 2221 and Pahl & Beitz's Konstruktionslehre are good examples of well-known structured product planning models, however these models have traditionally taken product life-cycle perspectives lightly (Hepperle et al. 2011). Instead, for numerous reasons, life-cycle-oriented approaches have arisen. Of particular interest is modelling the environmental impacts of product life-cycle. Some recent trends have forced product designers and developers to consider a more holistic product life-cycle, including a shift towards Product Service Systems (PSS), the increasing importance of Corporate Social Responsibility (CSR) and tightening environmental legislation (Gopsill et al. 2011).

Generally, product life-cycle is a series of phases through which a product passes during its life span, however there exist many different approaches for distinguishing these different stages depending on the product type. A typical product might have life-cycle stages similar to those illustrated in figure 1.4, where the life-cycle is divided into Beginning of Life (BOL), Middle of Life (MOL) and End of Life (EOL). Each phase consists of more detailed sub-activities. (Dimitris Kiritsis et al. 2003, cited in Shin et al. 2010.)

Notable in Kiritsis et al. (2003) approach is the integration of customer requirements and product life-cycle requirements into the product life-cycle system. Customer requirements are seen as a feeder input to the system. The life-cycle requirements are both seen as an input to the system and a result of the life-cycle process. (D. Kiritsis et al. 2003, cited in Shin et al. 2010).

Another suggested division of product life-cycle is provided in Olesen's (1992) Disposition theory (see figure 3.15). In this approach there is emphasis on the different functional areas of a company to which the product life-cycle is divided.

Although the divisions include the whole life-cycle of the product and the aim in life-cycle modelling is to gain transparent look holistically, in most cases the life-cycle orientation means focusing only on several life-cycle requirements. In this instance DFX becomes relevant once again. As an example, Shin et al. (2010) provided a collection of design requirements for the three different life-cycle phases (figure 4.1) BOL, MOL and EOL.

Product lifecycle phase		Examples of lifecycle requirements
BOL	Design	Design requirements related to the technical restrictions in production
	Production	Design requirements for ease of assembly
		Design requirements for ease of disassembly
		Design requirements for environmental consciousness
		Design requirements for reliability
		Design requirements for health and safety
MOL	Usage	Design requirements related to normal usage conditions
		Design requirements related to usage environment
	Maintenance	Design requirements related to warranty conditions
		Design requirements related to warranty period
		Design requirements for ease of maintenance
EOL	EOL product recovery	Design requirements related to product deregistration process
		Design requirements for product reuse
		Design requirements for product recycle
		Design requirements related to environmental restrictions
		Design requirements for ease of disassembly
		Design requirements related to take-back policy

Figure 4.1. *DFX requirements divided into different product life-cycle phases* (Shin et al. 2010).

Depending on internal and external requirements, a company concentrates on a specific DFX, prioritizing the order of actions in life-cycle requirements accordingly (Shin et al. 2010). The fundamental mindset in life-cycle orientation is that the product characteristics affect all of the product life-cycle activities as in figure 1.4 can be seen.

4.1.2. Approaches for product life-cycle information modelling

Many different ways exist to model and analyse product life-cycle elements. The following is a short summary of typical approaches used in life-cycle modelling.

Quality Function Deployment (QFD) has been widely accepted method to support effective product conceptual design and consideration of product life-cycle requirements (Shin et al. 2010; Timo Lehtonen et al. 2012; Hepperle et al. 2011). QFD is a matrix-based method traditionally used in analysing the relationships between customer requirements and product characteristics during the product's conceptual design. Another well-known approach, House of Quality (HOQ), is a modification of the QFD model using a graphically house-like correlation technique. Currently, several different modifications of the original QFD model exist, such as Green QFD and Life-cycle Design (LCD), which each emphasize specific product life-cycle factors. However, QFD and its derivatives are strictly limited to quantitative correlations and in many cases are considered too simple for more complex product life-cycle analysis. (Shin et al. 2010.)

4.1.3. Examples for product life-cycle modelling

Olesen's (1992) approach to depicting product life-cycle effects and dispositions is a score model that reflects decisions made in the product development to the overall product life-cycle. The score model is based on the seven virtues of costs, throughput time, quality, efficiency, flexibility, risk and environment (see figure 4.2). In the figure, the product's structure is changed to improve transportability. This change then affects the scores gained in the seven virtues. The score model is one proposal of how to guide the early state of product development process.

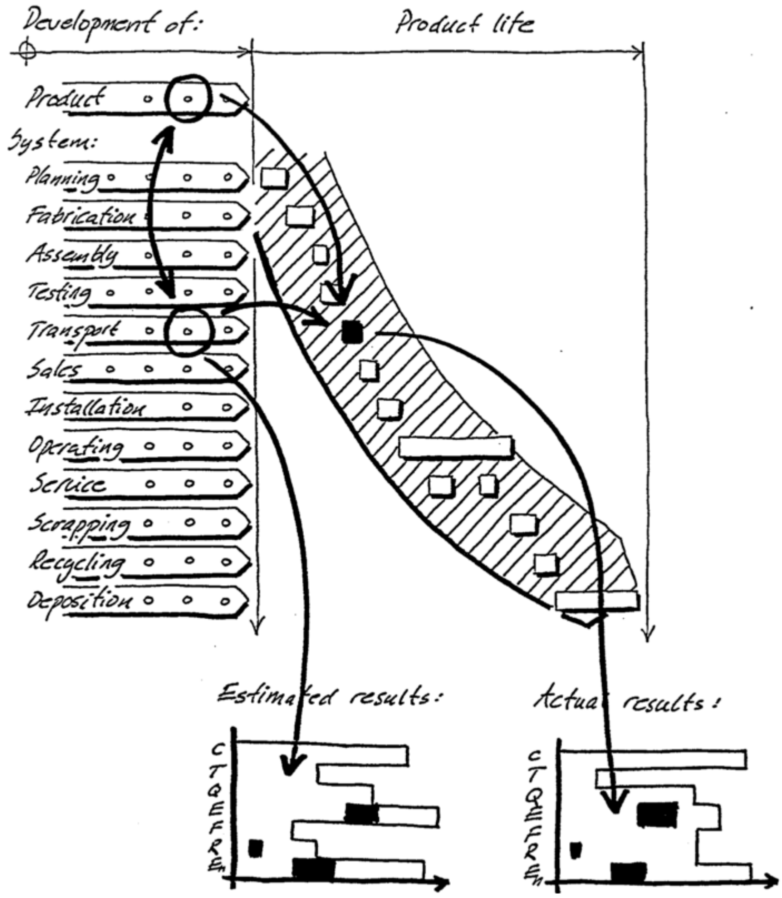


Figure 4.2. *Life-cycle score model according to Olesen* (Olesen 1992, p.60)***.***

Hepperle et al. (2011) presents a life-cycle-oriented approach that can also be used to support the early phases of an innovation process. The approach identifies and analyses goal interrelations against future demands and potentials in different life-cycle phases of a product. This is illustrated in figure 4.3. The approach starts on the right side of the figure with demands, which are transformed into goals, and then simplified into core functions. Alternative solutions for the functions are then sought before a comparison between parameter ranges of solutions is undertaken. Furthermore, the relationships between the different elements belonging to different life-cycle phases can be analysed. (Hepperle et al. 2011.)

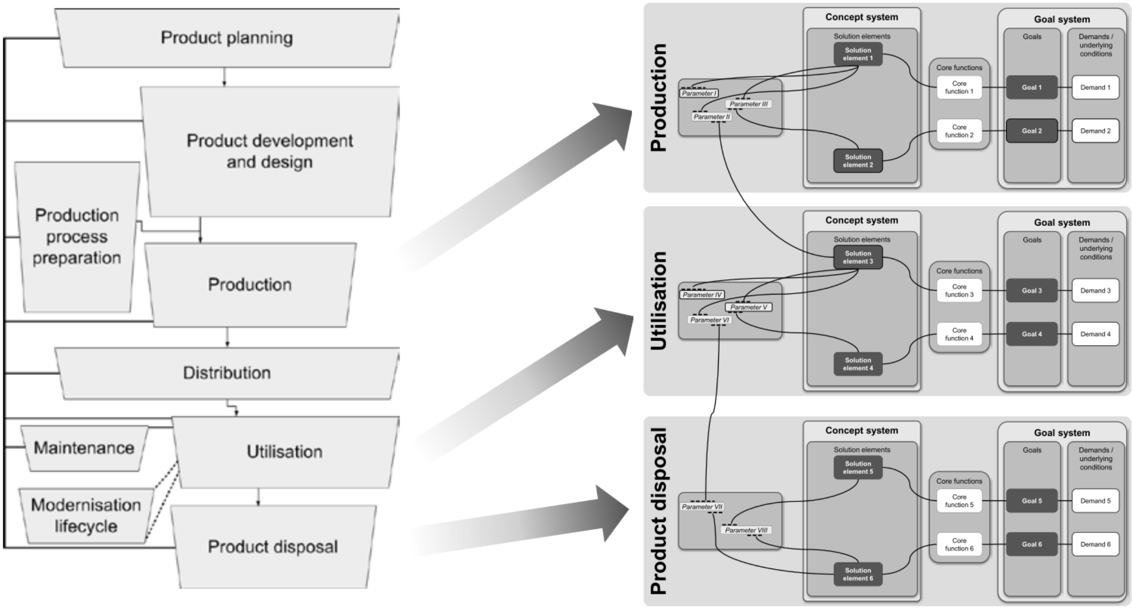


Figure 4.3. *Life-cycle-oriented approach for product planning* (Hepperle et al. 2011).

A graphical model makes it easier to identify conflicting goals and unexpected interrelationships (dispositions) between design characteristics in different life-cycle phases. This supports decision making in the early stages of product development. (Hepperle et al. 2011.)

Shin et al. (2010) uses an extended version of House of Quality (HOQ) to collect and depict relationships between engineering characteristics, customer requirements and product life-cycle requirements (see figure 4.4).

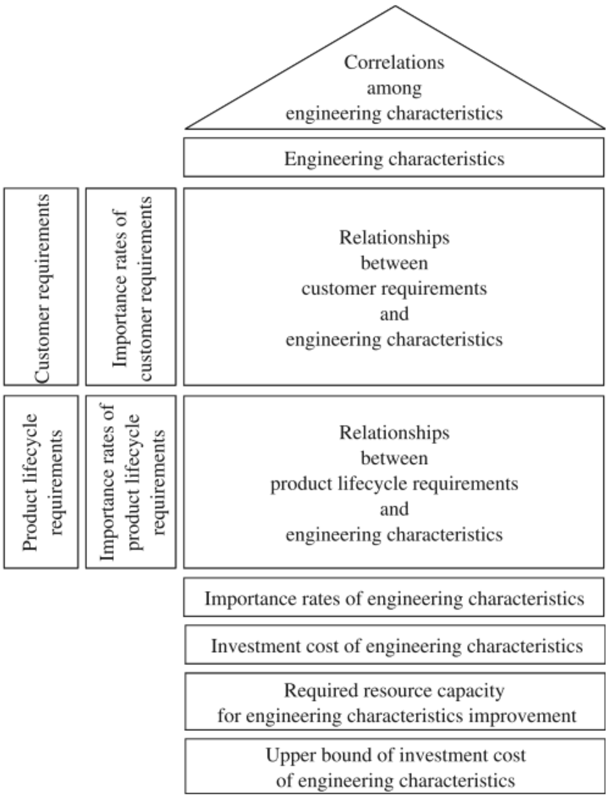


Figure 4.4. *An extended HOQ for life-cycle modelling* (Shin et al. 2010, p.869).

In the above model, correlations among engineering characteristics aim to identify compatibility between different engineering characteristics. Product life-cycle requirements are gathered from strategically important life-cycle activities. The extended section of HOQ includes of the following, ‘importance rates of engineering characteristics’, ‘investment cost of engineering characteristics’, ‘required resource capacity for engineering characteristics improvement’ and ‘upper bound of investment cost of engineering characteristics’. This helps product designers choose the right design characteristics for the right customer and life-cycle requirements. (Shin et al. 2010.)

The IPPD research group at TUT has undertaken preliminary work in product life-cycle modelling incorporating Olesen’s dispositional thinking. One of the projects undertaken was done with the co-operation of a Finnish boat manufacturer. As an outcome an early phase concept analysing tool was developed.

A starting point for the tool development was Olesen’s Disposition Theory, Design Science and theories of product properties and characteristics. Based on those theories, the tool works on the assumption that a design with a specific property will cause a particular behaviour when meeting an environment with a known property. A simple example: when a car that has tires developed for summer conditions meets winter conditions, a particular behaviour is evident caused by the natural laws. The hypothesis in this case is that, in general, expected behaviour can be formed based on earlier empirical findings, deduction from axioms or, as in the example, on natural laws. (Lehtonen et al. 2012.)

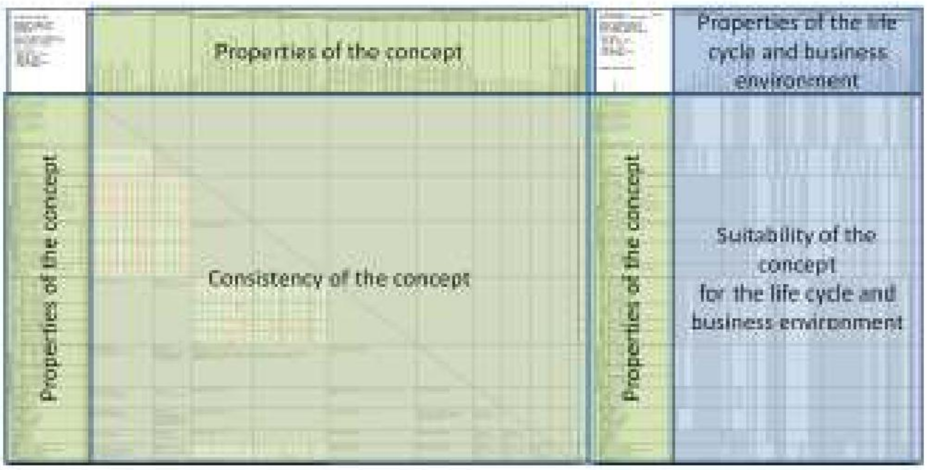


Figure 4.5. *Layout of the product concept analysing tool* (Lehtonen et al. 2012).

The tool itself is a matrix based-tool that depicts the behaviour of the concept reflecting it to a business environment. The layout of the tool can be seen in figure 4.5. The analysis process is divided into the following four steps:

1. Clarification of the properties of the concept
2. Clarification of the properties of the life cycle and business environment
3. Evaluation of the consistency of the concept

4. Evaluation of the suitability of the concept for the life cycle and business environment.

(Lehtonen et al. 2012.)

The properties of the concept in the boat industry case were divided into four main groups - materials, manufacturing methods, fastening methods and physical properties (Lehtonen et al. 2012).

The properties of the life cycle and business environment represent value chains, and processes and services. Preliminary work was undertaken before these properties could be identified. (Lehtonen et al. 2012.) For this purpose Company Strategic Landscape (CSL) model was used, which has been developed by the research team at TUT. CSL-model collects important elements relating to product development operations and to the production of a company. It also depicts company's business operations and organisational elements. Figure 4.6 shows the division of elements in the model. (Lehtonen 2007.)

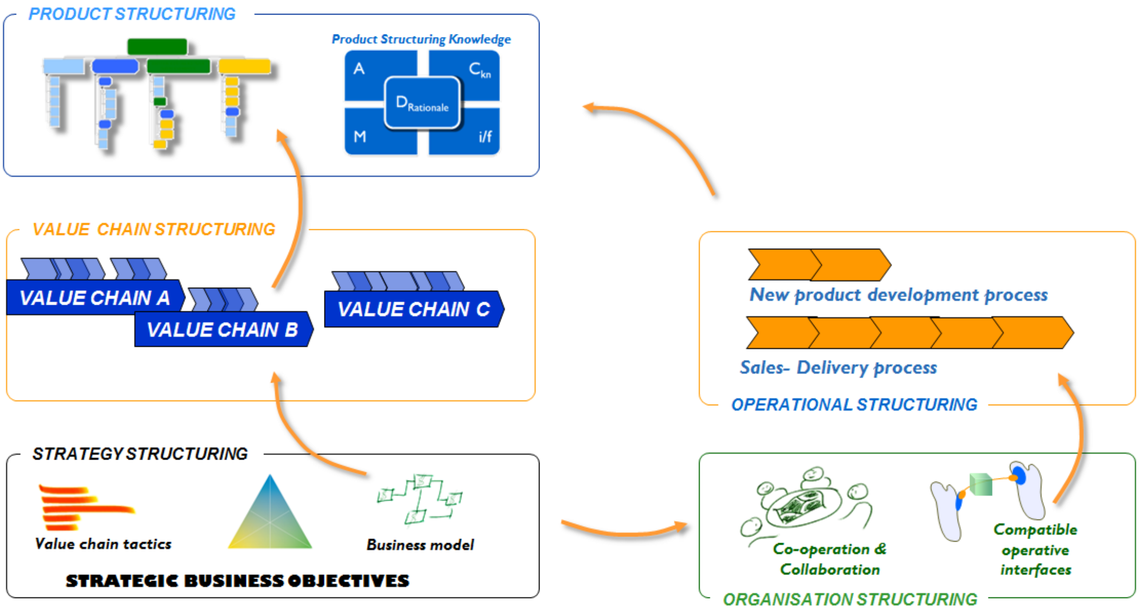


Figure 4.6. *Elements of the CSL model* (Lehtonen 2007).

As an outcome, the CSL model describes the key issues for structuring of a product, thus providing a framework to optimally develop product structure in relation to company's process (Lehtonen et al. 2012). For this particular example, CSL was used to structure the main elements of the order-delivery process of boat manufacturing.

After collecting the properties of the life cycle and business environment with the help of CSL, the evaluation process can be started. In the evaluation the consistency of the concept and the suitability of the concept for the business environment are analysed by marking dependencies into a matrix. In the evaluation, the focus is on understanding the connection between product structure and the delivery process and supporting the early concept development of a product. (Lehtonen et al. 2012)

4.2. Complexity management approaches

Complexity management is a broad framework widely used in controlling a variety of a company's business activities (Lindemann et al. 2009). This research views complexity management from the product and production development perspective.

From a product point of view, Weber (2005) divides complexity into five different dimensions; numerical, relational, variational, disciplinary and organisational (figure 4.7). These five dimensions are grouped into product/system level and process level.

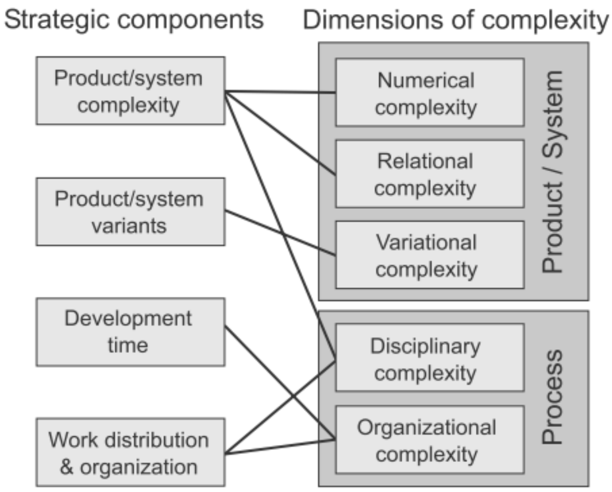


Figure 4.7. *Five dimensions of complexity* (Weber 2005).

Numerical complexity relates to the number of components in a system, whereas relational complexity concentrates on the dependencies between components. Variational complexity explains the amount of variants of a system, disciplinary complexity relates to the number of disciplines involved and finally, organisational complexity links to the allocation of work. (Weber 2005.)

There are different established strategies considered effective in complexity management, including:

- acquisition and evaluation
- avoidance and reduction
- management and control

Complexity and complexity management is relevant to this thesis given the complex nature of product structures and the nature of multidisciplinary development environment throughout different functional areas of a company. However, this thesis only draws on complexity management tools as they enable the acquisition, depiction, evaluation and management of dependencies within systems.

This chapter presents two of the most common approaches to execute these complexity management strategies; graph approaches and matrix-based approaches, which includes Design Structure Matrix (DSM), Domain Mapping Matrix (DMM) and Multi Domain Matrix (MDM).

4.2.1. Graph approaches

Graph approaches are based on Graph Theory, which according to Lindemann et al. (2009), forms the basis for system representations and include characteristics such as trees and cycles, and structural attributes (e.g. connectivity and coloring). Numerous algorithmic problems are applications of graph theory. Matrix-based solutions such as DSMs also pertain to this area and will be addressed separately in the following section.

Modern design problems can be supported with the use of visual representations to improve methods of communication, interpretation of information and systematic evaluation (Tilstra et al. 2010). Graph approaches may include matrices, graphs such as directed graphs, diagrams and charts, to present and analyse information in different ways (Lindemann et al. 2009). Different graph approaches exist to meet the right user and environment requirements (Kohn & Lindemann 2009).

4.2.2. Matrix-based approaches

Matrix-based approaches, such as QFD and HOQ, are popular and widely used applications in industry. (Lindemann 2009). The purpose of matrix-based tools is to illuminate a structure and aid in the design of products, processes and organisations. Commonly matrix-based tools are associated with DSM. (Browning 2001.) It is therefore natural to begin with presenting DSM and subsequent approaches.

DSM was first introduced by Donald V. Steward in the 1960s and was known as Design Structure System (Steward 1981; Browning 2001). It used terms such as dependency source matrix, dependency map, interaction matrix, and precedence matrix, all of which link it with DSM. Since Steward's research in the 1960s, the use of DSMs has been increasingly popular in many types of system and design analysis in both research and industrial practice. (Browning 2001.) Common areas include product development, project planning, project management, system engineering, and organization design (Brady 2002).

DSM is based on N-square matrix, where the different dependencies of elements in a system are represented and analysed (see figure 4.9). Elements, or units, are listed identically in rows and columns. An "X" in a row indicates a dependency, in which information flow is seen between two elements. (Steward 1981.) An "X" represents a binary dependency, but also numerical dependencies are used, which indicate for example the strength of a relationship between two elements (Lindemann 2009). The reading direction in a matrix is from the element named at the top of the column to the element labelled on the left of a row. For example in figure 4.8 we can see that element 1, 'passenger capacity specification' does not require any elements as preliminary information, whereas the second element, ‘size and aerodynamics’, requires the elements 1, 3, 7, 11 and 12 as preliminary information.

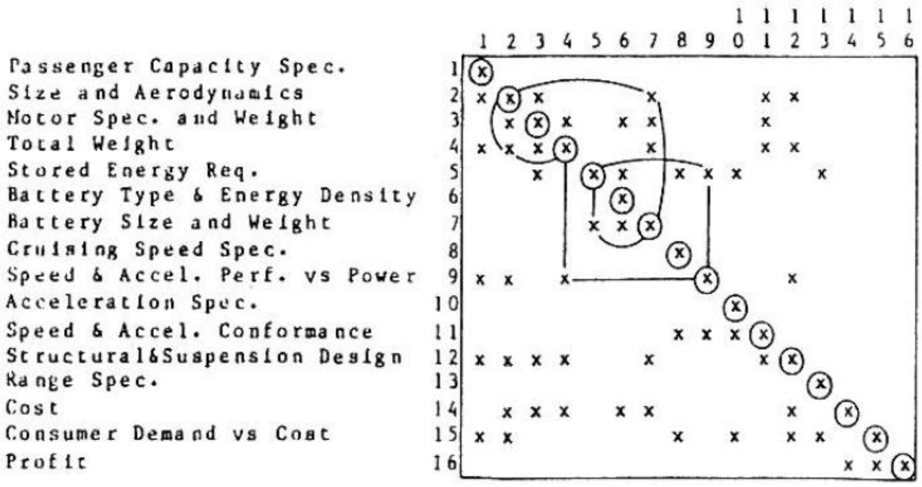


Figure 4.8. *Design Structure Matrix example* (Steward 1981).

DSMs are divided in to two different main categories; directional matrices or static matrices. The fundamental difference is that in the directional matrix the relations are time-based, whereas the static matrix only captures relations between system elements that exist simultaneously, such as components in product architecture (Browning 2001). Browning divides these categories further into four different DSM types: Component-Based, Team-Based, Activity-Based and Parameter-Based (table 4.1).

Table 4.1. *DSM types* (Browning 2001)

	DSM Type	Representation	Application	Integration Analysis
Static	Component-Based or Architecture DSM	Components in a product architecture and their relationships	System architecting, engineering, design, etc.	Clustering
	Team-Based or Organisation DSM	Individuals, groups, or teams in an organization and their relationships	Organization design, interface management, application of appropriate integrative mechanisms	
Time-Based	Activity-Based or Schedule DSM	Activities in a process and their inputs and outputs	Project scheduling, activity sequencing, cycle time reduction, risk reduction, etc.	Sequencing
	Parameter-Based DSM	Parameters to determine a design and their relationships	Low-level process sequencing and integration	

The table above indicates the diverse advantages DSM provides in different problem areas. DSMs also enable several analysis methods based on algorithmic approaches such as clustering and sequencing presented in the table above. Clustering in a static matrix organises elements into clusters, where for example interfaces between components can be analysed. Sequencing rearranges elements such as activities in a product development project, in to rational order reducing design iteration, and enabling activities to be planned and completed simultaneously when possible. (Browning 2001.) Other methods of analysis are banding, partitioning and tearing. These all help to manage elements and their dependencies, and help to simplify complex dependency structures (Lindemann et al. 2009).

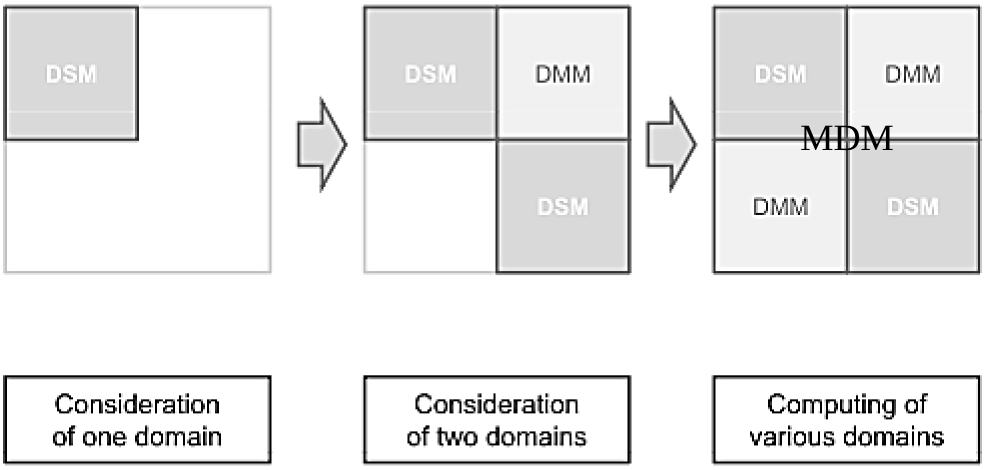


Figure 4.9. *The evolution from DSM to MDM* (Danilovic & Browning 2009).

A symmetrical matrices, DSMs face constraints especially when analysing dependencies between different domains. Other matrix-based approaches have evolved from DSMs to assist in analysing dependencies between multiple domains. These include Domain Mapping Matrix (DMM) and Multi Domain Matrix (MDM). (Lindemann et al. 2009.) Figure 4.9 illustrates the links between DSM, DMM and MDM.

DMM captures dependencies between two different domains and is an extension of DSM. It uses the same basic principles as the DSM and captures binary or numerical dependencies in a specified order of information flow. DMMs are rectangular matrices, in which element list on the left of the rows and top of the columns represent different domains. (DSMweb 2012.) QFD and HOQ are examples of DMMs.

Multi Domain Matrix (MDM) is a combination of DSMs and DMMs. The advantage of an MDM is that it can analyse a single domain separately as a DSM. It combines the advantages of both DSM and DMM and can use analysis algorithms from all presented matrix types.

In this thesis matrix-based approaches are used as a supportive tool to map and analyse product structure information. For product structuring it facilitates the acquisition and interpretation process, which is significant when examining complex structures.

4.2.3. Example of graph & matrix-based approach

IPPD research group has developed a tool, Disposition Modelling (DiMo), which combines graph approaches such as DSM and directed graphs (figure 4.10) to model and analyse dependencies, or dispositions between elements in systems involving product development. The purpose of the tool is to facilitate the decision making process of product and production development teams using approaches which enable effective interpretation of information and common language (Halonen et al. 2012).

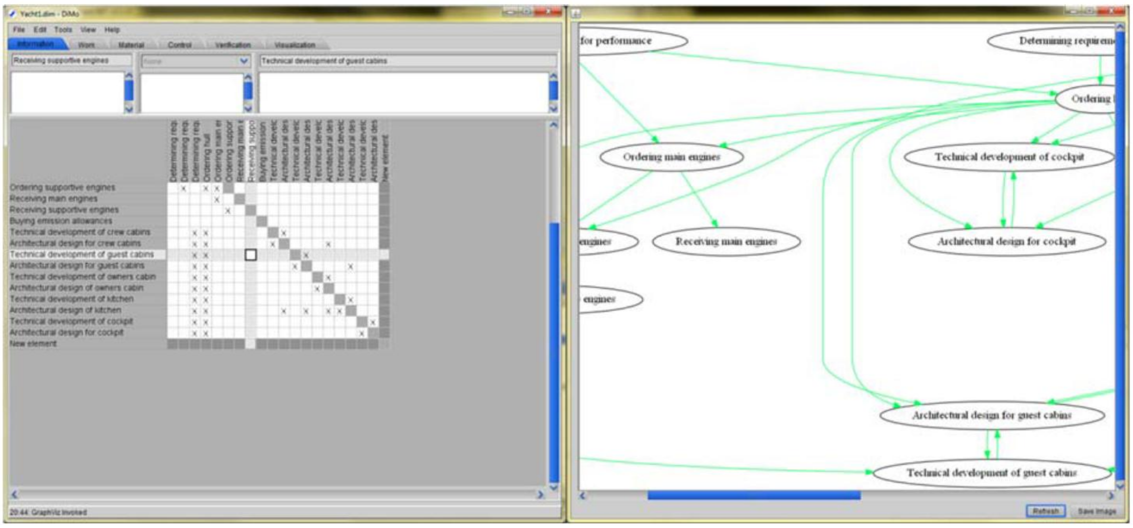


Figure 4.10. *Layout of the DiMo-tool.* (Halonen et al. 2012.)

Information acquisition can be done by capturing all the relationships between different elements in the DSM. The order of the elements can be reorganised by using the partitioning algorithm before information is interpreted visually using a directed graph function.

An example of the tool being used would be a typical product development project. In this instance, a work breakdown structure is listed into the matrix. Next, the relationships between the activities are captured using the directed graph to validate the quality of information and once all the relevant elements and their time-based relationships are inserted in to the DSM, the most optimum sequence of the activities can be organised using the partitioning algorithm. Possible loops in the DSM indicate parallel activities, which are needed to be done simultaneously. Information from the tool can then be visually presented in a variety of forms, such as Gantt charts, to schedule the project in the given sequence.

This computer based tool is also part of the broader research area to which this thesis contributes to, aiming to be the supportive tool for the results of this thesis in the future research.

4.3. Flow Model in integrated product and production development

Takahiro Fujimoto states that product development is the creation of design information whereas production is the transfer of this information to products. He proposes that product development and manufacturing should be considered as a continuous product creation process. Furthermore, this creation process should be modelled as a flow of knowledge. Fujimoto uses an automobile as a case study, where the starting point for creating a new automobile is intention. This includes the understanding of what properties a product should possess. Later on these properties guide the creation of new knowledge and eventually leading, if successful, to desired properties of a product. (Fujimoto 2007). This thinking has a lot of common with the Theory of Dispositions by Olesen. The moment when product property is decided and the moment when the behaviour emerges is called dispositional mechanism (Lehtonen et al. 2012).

Lauri Koskela represents similar kind of flow thinking in his doctoral thesis whereby product development and production is seen as a unified flow. According to Koskela, development as a flow process includes four stages at which information is divided into four different sections: transformation, waiting, moving and inspection. Transformation is seen as the only true designing when others are considered as waste which should be avoided (Koskela 2000).

FLOW	DESCRIPTION	RESULT
Knowledge	Transformation and move of design information	Documentation
Work	Work for value increase	Added value
Material	Raw materials and outsourced product parts	Added material
Control	Controlling events	Management of waiting and inspection

Figure 4.11. *Description of the elements in the flow model, (*Attained from Lehtonen et al. 2012).

The IPPD research team at TUT has used this flow thinking in several case studies to reveal design rationale in decision making. In their model, the transformation presented by Koskela is divided into four specific flows (figure 4.11). These flows are:

1. Knowledge/Information flow
2. Work flow
3. Material flow
4. Control flow

(Lehtonen et al. 2012)

Knowledge flow represents activities in transforming and moving design information. Documentations such as 3D models are an outcome from this flow. Work flow shows activities that increase product's value. Examples of this are manufacturing and assembly activities, which add value to the product. Material flow includes the flow of raw materials and outsourced product parts. Control flow represents activities for managing the timing and inspection with control events. It also answers the question of who is managing and controlling the element. (Lehtonen et al. 2012)

In IPPD research group some work has already been done in the area of flow modelling. In the following, two examples of these previous works will be represented. Firstly, a production process flow model is presented, developed and used in a case study in the boat manufacturing sector. Secondly an approach to depict the optimal design and manufacturing process to achieve a desired outcome in a product from automobile industry is presented.

4.3.1. Flow Model of production process in boat manufacturing

This project was completed for a Finnish boat manufacturing company and aimed to develop their production process by using the flow model to model their production process. The flow model was done in Microsoft Excel and is illustrated in figure 4.12. On the right side of the figure is the breakdown of the parts in a boat also representing the different stages of specific part's activities. Each activity, hence each row, includes work, material, information and control flows. Work flow consists of the description of the current state of the activity, the description of desired state, working hours, number of workers and duration times. Material, information and control flows in each row include description of the current state, description of the desired state and the desired distribution of work. An analysis of the costs related to each element and the value creation properties were also included on the left side of the figure.

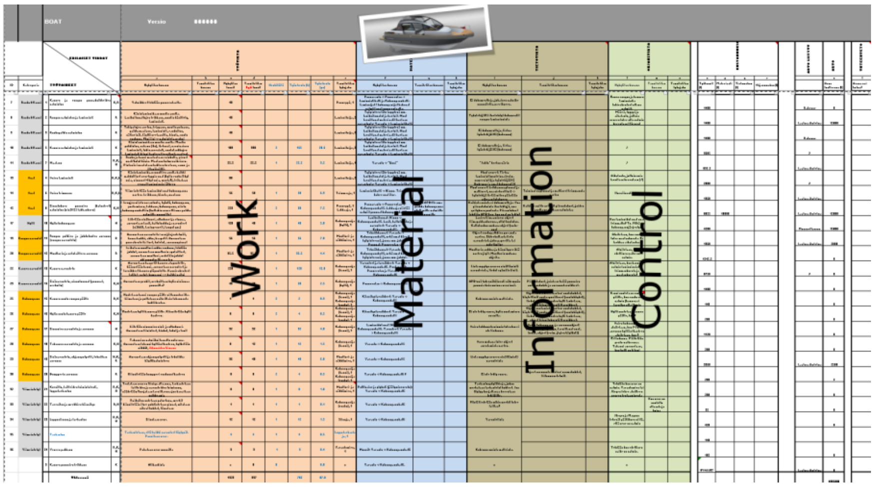


Figure 4.12. *Layout of the tool for production process flow modelling* (Lehtonen 2008)

This model supports the understanding of the production process and identifying possible flaws within these four flows. It answers the questions: How do the costs behave in the production process, which activities actually add value and which are pure expenses?

This depiction model has been also integrated into a more general tool used for educational purposes at TUT. The tool has been successfully used in student projects, whereby students manage a product development process of a given case within their course.

4.3.2. Flow Model of a combined product and process

This research project is done in collaboration with a company that manufactures special cars and is still an ongoing project. Work is based on the principles defined by Fujimoto and Koskela (Lehtonen et al. 2012).

The model uses a Disposition Modelling tool (DiMo) as a documentation and analysis base, with features from a design structure matrix (DSM) (figure 4.9) (Halonen et al. 2012). The combined product and process flow description model depicts the knowledge in DiMo. The knowledge includes the generic engineering bill of materials (GEBOM) of a car and all the development phases needed before reaching the final element in the matrix. GEBOM and the phases are captured in the DSM preferably in the order they are planned to be produced and assembled. After this the technical interdependencies are collected and the elements are captured into four different flows provided by the flow model. (Lehtonen et al. 2012.)

The core of the model is documenting the maturity level of each design element. This maturity is a combination of three aspects. The first aspect is, how complete is the design in the element that is under inspection, the second is how complete are the predecessors of the inspected element and the third, is how do the properties of design proposal fit to the wished properties. (Lehtonen et al. 2012.) See figure 4.13 for the summary of maturity levels.

MATURITY OF DESIGN	
Design Readiness	How complete is the design?
Design Creativity	How complete are predecessors?
Design Compliance	How well are the properties of design proposal within wished properties?

Figure 4.13. *Maturity of design* (Attained from Lehtonen et al. 2012).

During initial development, only one flow was used to depict the maturity level of a product using a stage gate approach. The chosen flow was information, a natural and preferred starting point for the model, because different knowledge related documents, such as CAD files, could be easily compared to the desired properties through the PDD framework. The information completeness is modelled through information elements, tasks that are needed to create the information elements and relationships between these elements and tasks. (Pakkanen et al. 2012)

This model is assumed to become a practical tool in the case company. The maturity calculation instead of fixed stage gate approach, is seen as leaner, more agile and because of these, in many cases, even faster and more cost effective. (Lehtonen et al. 2012)

4.4. Product configuration and modularity

Presented below is the state of the art of product configurability, which, in this thesis, works as a case study area for the disposition model. Product configuration will be examined first, followed by modularity.

4.4.1. Product configuration

Product configuration is seen as one operational mode of mass customization. In short, product configuration is to deliver products customised according to individual requirements. (Juuti 2008.) Furthermore, a configurable product refers to a product from which individual product variants can be formed; hence a product family which uses pre-designed elements such as modules (Juuti 2008; Lehtonen et al. 2003). A specified configuration model will determine the guidelines for creating variants for a product (Juuti 2008) (see figure 4.14).

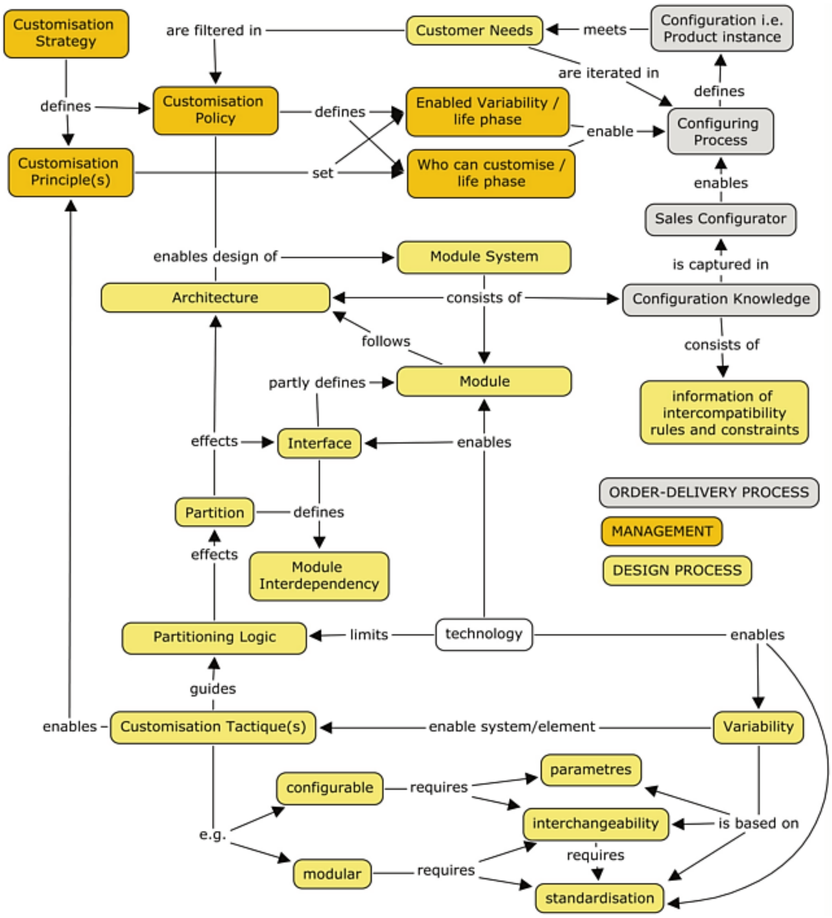


Figure 4.14. *Configurable product key concepts and their relations* (Juuti 2008).

According to Juuti product structures can be divided into four different product structure types (Juuti & Lehtonen 2006). These are, one-of-a-kind product structure, standard product structure, configurable product structure and partly configurable product structure (see figure 1.3). From these we will focus on the latter two types.

A configurable product structure has the following three goals:

- Elimination of engineering design in order-delivery process with variability
- Commonality by re-use of design
- Product synthesis.

A configurable product structure includes standard parts and configurable parts. Variability comes from re-using a combination of standard parts, modular parts and/or module system parts.

A partly configurable product structure has the following three goals:

- Product level synthesis
- Commonality by re-use
- Variability through configuration or modularisation

Partly configurable product structure includes standard parts, configurable parts, one-of-a-kind parts and partly configurable parts. Therefore it is a combination of all the other product structure types.

4.4.2. Modularity and modular system

A number of different definitions can be found for modularity from different periods (Lehtonen 2007). In modularity research, Borowski's Baukastensystem is often considered as a starting point for modular structures.

Karl-Heinz Borowski was the first one to define a modular system calling it as Baukastensystem. It consists of standardised elements that can be joined together following pre-defined rules. Borowski represents nine different cases as types of Baukastensystem. (Borowski 1961, cited in Lehtonen 2007.)

In more detail, Baukastensystem is defined as a system that consists of elements that come in different sizes within the desired solution level. An element is seen as an indivisible entity within the system. Furthermore, Borowski defines a constructional element as an element belonging to a configurable system. (Borowski 1961, cited in Lehtonen 2007.)

Borowski's definition of Baukastensystem has a few important aspects that are relevant to a modular system even though some of his definitions and examples would not qualify in today's knowledge for modular systems. Modular systems use pre-defined, standardised elements that have a considered interface. However, in Baukastensystem non-modules are also accepted into the system resulting in combinations of modules and non-modules. Thus, partially-configuration is also considered to be part of a modular system. Borowski did not use the word module at that time, preferring constructional system and a non-constructional system to describe the elements. (Borowski 1961, cited in Lehtonen 2007.)

Lehtonen defines a module with the following two criterias:

- It has a defined interface, which specifies its connection to other modules
- It is a member of a set of elements or sub-assemblies that create a module system

This definition is also known as M-Modularisation, named by Lehtonen. (Lehtonen et al. 2003.)

4.4.3. The Flow of Product Structuring Knowledge in Manufacturing

Dr. Tero Juuti introduces a flow model for a configurable, manufacturable product. This model has been structured from data gathered from an interview with Juuti. Information in this model is based on his experience working in the Finnish manufacturing industry and on his past work done at TUT since the 1990s. The model can be found from Appendix 1. (Juuti 2012.)

In the model, the whole life-cycle of a configurable manufacturable product is structured into a dependency graph. Following the principles of flow model presented earlier, the phases of product life-cycle are then divided into four different streams; material, information, work and control. In addition, the model depicts elements belonging to the gained value of the product, and has a distinct development process for the modules used in the configuration system. The model includes the following distinctive criteria for product structure information: Product Structure Division Logic, Modular Architecture, Interface Descriptions, Modules, and Configuration Information. (Juuti 2012.)

This model will be used in this thesis as a guideline to analyse the differences of dispositional effects between a partly configurable product and a configurable product.

4.5. Synthesis for preliminary PLDM

The preliminary explanatory model, PLDM, is compiled from the information gathered from the theory basis and state of the art. The Preliminary PLDM is described from two viewpoints. First is the general description of the model and its elements, and secondly, a description of implementing PLDM in practice. Later, this preliminary version of the PLDM concept is employed in the case study.

The PLDM is a thinking model, or a learning system, in which the outcome is a design rationale to support decision making in integrated product and production development, and in management. Design rationale provides essential knowledge for designers and managers, of the product, product’s life-cycle and the relevant elements that influence the product and production development. With a cyclic learning system, similar to SSM (Checkland 1985), PLDM allows active and continuous improvement in the product’s development, by providing understanding of dispositions.

In the PLDM artefact is used as a general and an abstract term for an object made by humans or an object of doing. It is chosen to clarify and avoid confusions in what refers to the general description of the PLDM and what refers to a product in the case study. Thus, in examples and in the case study, the term product is consistent with the term artefact.

The PLDM is an artefact-oriented approach, in which artefact is seen as the starting point for the cyclic continuous development process. The model uses Weber’s (2012) PDD process as a central base for the process, including all of its elements. The PLDM also includes artefact life-cycle context and artefact life-cycle characteristics as an essential part of the process. This is a significant extension to the PDD process, as the artefact life-cycle is seen as an important force that continuously calls for reflection and updating the desired artefact properties. The artefact life-cycle entity follows the principles presented in life-cycle modelling and Flow modelling in the state of the art. The model is illustrated in figure 4.15.

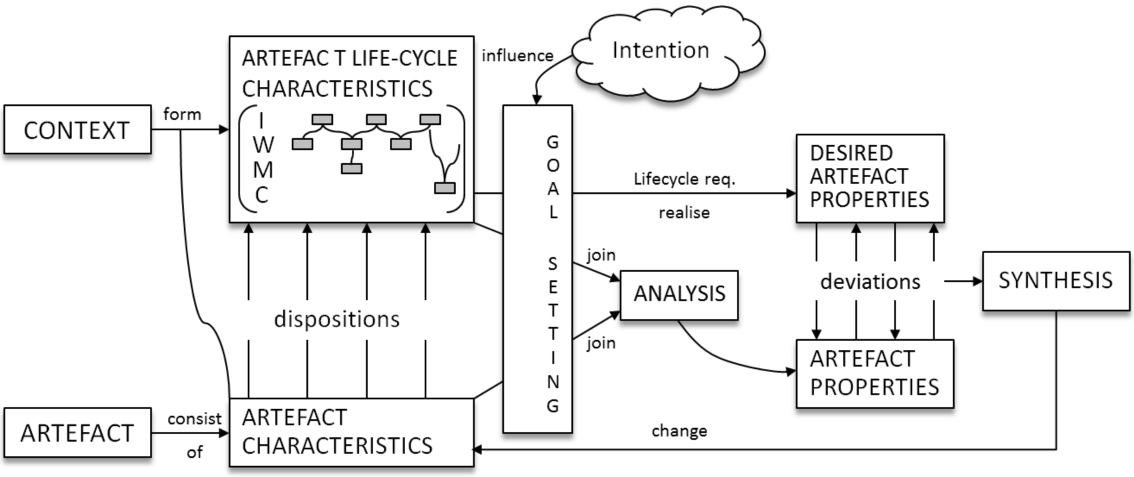


Figure 4.15. *Preliminary concept for Product Life-Cycle Disposition Model.*

PLDM aims to provide a framework to model and manage dispositions in the process. Dispositions represent the inherent relationship and interaction between the artefact's characteristics and the artefact's life-cycle characteristics wherein changes or influences to one entity directly effect and influence the other. This differs from Olesen's (1992) disposition theory significantly, as Olesen defines dispositions as activity-based relationships between two activities from different functional areas. However, in both, the basis of the fundamental meaning of a disposition, is that it is a natural phenomenon and seen to be challenging to acknowledge by companies.

As mentioned earlier, PDD process plays a central role in the PLDM process. The artefact consists of artefact characteristics, which, when taken up with environment, are realised in artefact properties. Through PDD's analysis-synthesis process, the properties are reflected to desired artefact properties. However, compared to Weber's (2012) cyclic process of PDD, in this model the significant difference is the presence of artefact life-cycle context and artefact life-cycle characteristics, which are distinguished from the external conditions and are part of the process. As in Weber's PDD process where desired artefact properties are fixed, in the PLDM the desired artefact properties change as the dispositions occur in the product life-cycle characteristics.

In the PLDM, the context refers to the environment within which an artefact interacts. In this context, artefact characteristics form the artefact life-cycle, and the life-cycle is seen through the information, work, material and control flows presented in the Flow model (Lehtonen et al. 2012). Artefact life-cycle characteristics are seen as the actual realisation of the life-cycle process, which consists of the elements of the four flows, such as tasks and information elements. The elements of the flow model are related to different life-cycle phases, as presented in the life-cycle modelling.

A significant element for the learning cycle is goal setting, which can be realised in a chosen DFX approach. Intention functions as a catalyst for the goal setting. The PLDM's analysis–synthesis process will be directed through the chosen DFX. It is chosen according to influences by artefact life-cycle requirements (Kiritsis et al. 2003), such as customer requirements, regulatory requirements, and external requirements outside from the life-cycle process. DFX provides scope to focus on the relevant elements and relevant properties to support the decision making process. The specified goal-based analysing is also relevant when modelling dispositions, as only few relevant dispositions should be focused from a great amount of dispositions.

The implementation of the PLDM in practice consists of preparatory work and dispositions modelling (see figure 4.16). In this context, the term product is used instead of artefact, to emphasise actual products that are part of the implementation. Preparatory work includes two main areas of mapping; mapping of product's structure and its characteristics, and mapping of product's life-cycle and its characteristics. For example, brownfield products can be started from both of the areas and many companies have already relevant raw data and knowledge to start with.

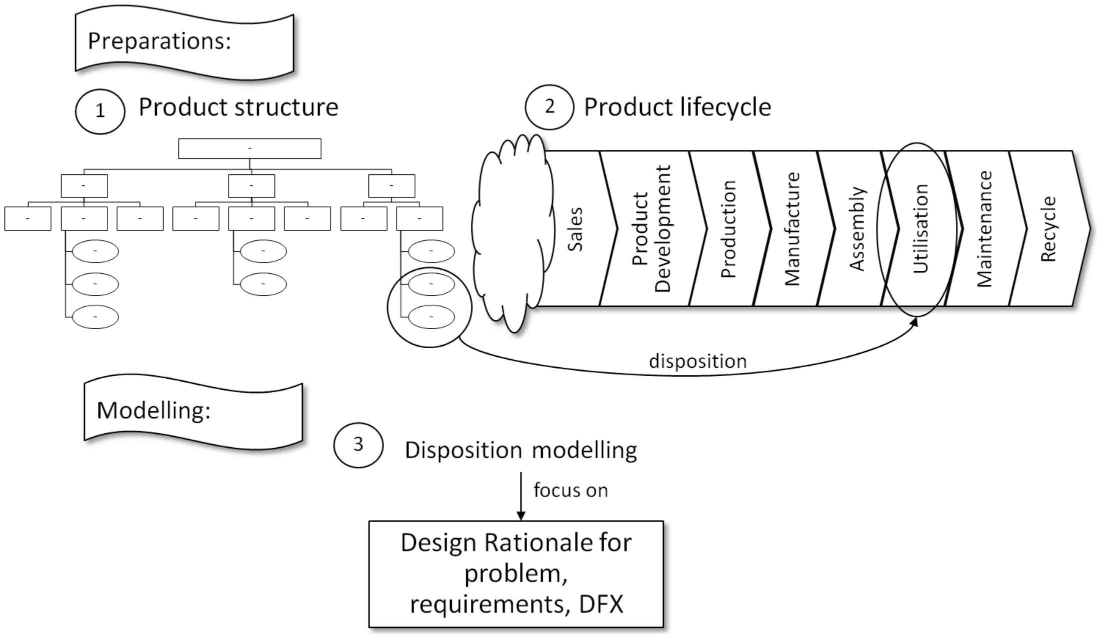


Figure 4.16. *Implementation of PLDM in practice.*

In this example, preparatory work is started by mapping the product's structure. Product's structure is mapped in alignment with Andreasen et al.'s (1996) demonstrated product structuring, from chosen points of view. Structure can be, for example engineering bill of materials, which is a complete list of all the components a product consists of, or it can be a broader description of product architecture and its characteristics. Matrix-based tools can be used to support the mapping process. The criterion is that all of the chosen characteristics are seen valuable for company's business, and contribute to the chosen target and DFX.

The second area of preparatory work is mapping the product's life-cycle. The way to depict product's life-cycle depends on the nature of the company. The mapping of product's life-cycle has to adopt to organisations culture and habits, which define the common language, organisational structures and type of the process depiction used. In general, the product life-cycle can be a typical order-delivery process including other life-cycle phases, such as maintenance, if necessary. Also the level of detail has to be decided before starting the modelling process.

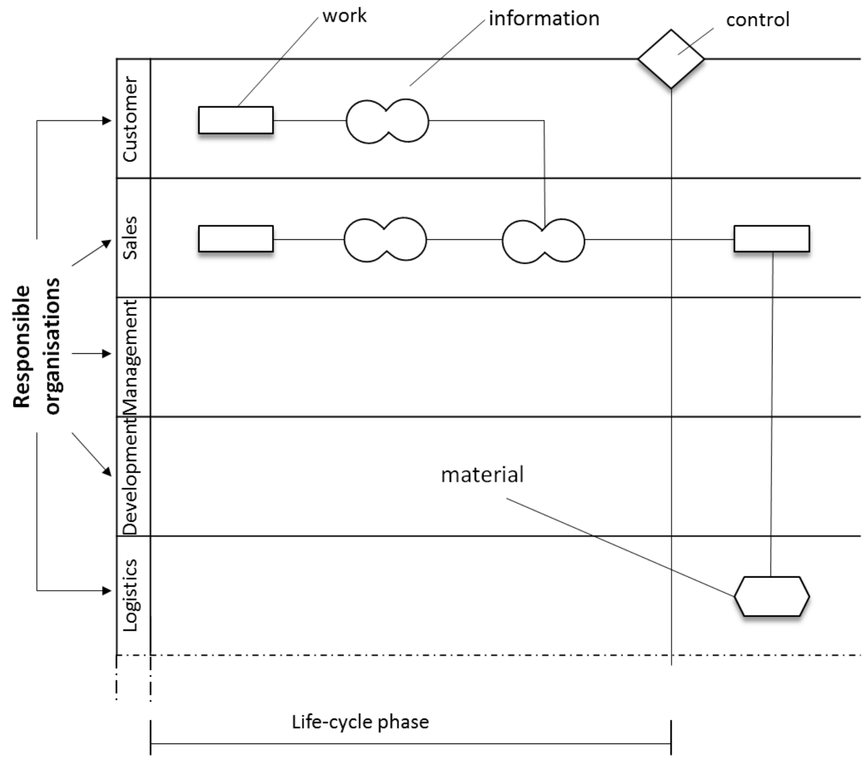


Figure 4.17. *Elements in a product life-cycle map.*

In a product's life-cycle description, life-cycle phases are divided into four flows of Flow Model, as described by Lehtonen et al. (2012). These flows are information, work, material and control. Activities that add value to the product are an example of work flow. Outcomes of activities can represent material or information flows. In addition to dividing the elements to these four flows, the elements are divided into company's organisational structure that represents one part of the control flow. The primary control flow elements are controlling tasks that determine whether process can proceed through a certain point, thus checking that all of the requirements in that particular checkpoint have been achieved. Figure 4.17 illustrates these four flows in a process map. Flows are depicted with different symbols and divided into responsible organisations. Also, in the map different life-cycle phases are separated.

After mapping the product's structure and life-cycle, actual disposition modelling can be started. As a starting point, there are two distinguished approaches to model dispositions. The first is to model from product characteristics, in which a question is formed: what kind of dispositions does this particular product characteristic affect in some specific life-cycle phase? The second approach is to start from desired dispositions in product life-cycle and begin by asking: what kinds of dispositions are desired in this particular life-cycle phase?

Once again, the focus and the purpose define what is being modelled. The starting point can be an identified problem in product's life-cycle, or a requirement that is identified from product's life-cycle characteristics. For this purpose a DFX approach is an applicable solution given the likeliness of a clear goal system (Hepperle et al. 2011). Modelling in this context might have a focus on a specific DFX and aims to find understanding of different solutions through a learning cycle. On the other hand, dispositions can be directly modelled analysing specific product characteristics and their effects on product's life-cycle.

Finally, disposition modelling consists of the preparation stage and modelling stage. Disposition modelling implements the PLDM into practice and provides a valuable learning cycle for the organisations responsible for product's life-cycle. Disposition modelling can aim to answer the question; does a specific product's characteristic fulfil the desired product's life-cycle properties?

4.6. Summary of the state of the art

This chapter has presented the relevant state of the art for the thesis. The presented state of the art plays a significant role in constructing the preliminary synthesis of the PLDM.

Firstly, the area of product life-cycle disposition modelling shows that there does not yet exist an application that provides a direct solution for the study. Potential approaches do exist in modelling and managing product life-cycles, and the knowledge and ideas of some of the applications such as Hepperle et al.'s (2011) life-cycle oriented approach, can be utilised in this study and especially in further studies.

In general, product life-cycle modelling does not conflict with the theory basis so far. It is clear that a product life-cycle can be divided into different phases and activities and, common phases can be found even among completely different products. Product life-cycle requirements can be approached through target-oriented DFX. Company, market and environmental forces, can be simply included as part of product life-cycle requirements.

State of the art demonstrated that the Flow Model, where the product life-cycle process is divided into four streams of information, work, material and control, has been already successfully applied in some industrial cases. With this reliability, this approach can be used as a core element of the PLDM.

5. CASE STUDY

This case study describes differences of characteristics and behaviour between partly configurable product structures and fully configurable product structures, in a chosen scope of product life-cycle phases. It addresses the primary aim of this thesis by answering research question three. It also tests the preliminary PLDM, with analysis and results drawn from it.

The case study was carried out with a Finnish manufacturing company as part of a Tekes project in spring and summer 2012. Tekes is a Finnish funding agency for technology and innovation. The project was conducted by comparing company's current partly configurable product families with a scenario of fully configurable product families. Figure 5.1 illustrates the relationships between the thesis and the case study, providing a roadmap for the working process.

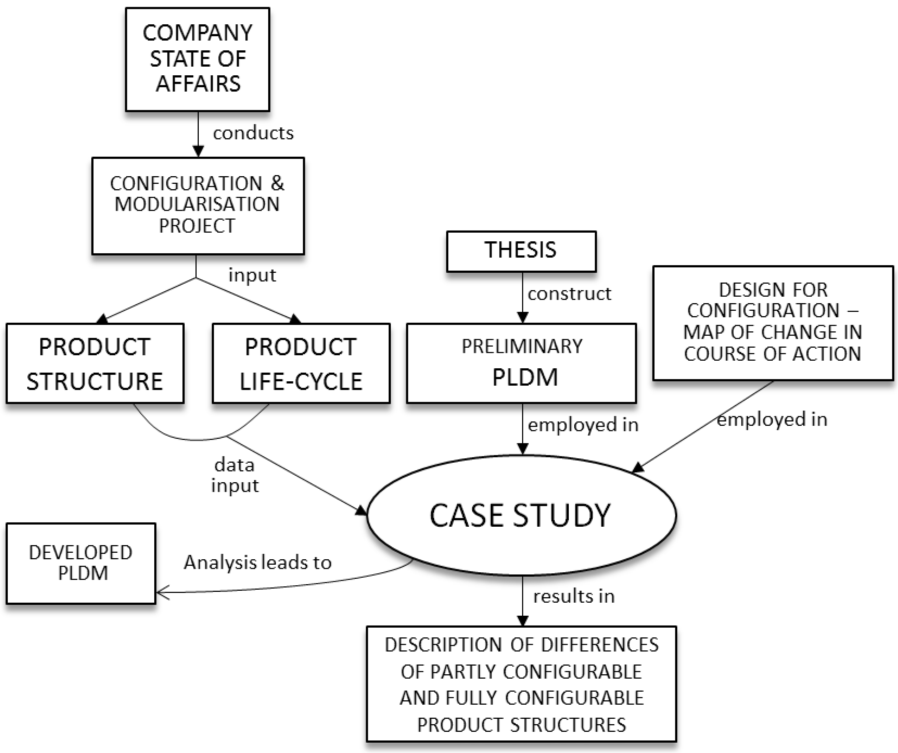


Figure 5.1. *Case study outline.*

Notable is that this case study is separate from the Tekes project, but was gathered from the data and experience of the project. The results of the case study are for research purposes at TUT.

5.1. Description of the company

The case company is a small-to medium enterprise, operating in the Finnish manufacturing industry. The company's production approach is make-to-order products offering deliveries for international customers across continents. The company's revenue is counted in millions.

The manufactured products are large in scale and the majority of customers are in the mining industry. As a project-oriented company, the products are partly configurable and include standard, configurable, partly configurable, and one-of-a-kind components. The products have a typical lifespan of 30-40 years so the company also offers services such as maintenance for its products and for similar kinds of competitor's products.

5.1.1. Current state in the company

The company faced rapid growth in order volumes leading to organisational growing pains. Originally a small supplier, a traditional machine shop, this growth has been a great challenge for the company. Even though revenue has increased rapidly, profit has not grown at the same pace.

Instead of profitable manufacturing, the growing number of orders and volumes has led to less efficient production systems. The company represents a traditional, project-oriented company that tailors order-specific products for customers. In the past, this customisation was easily managed by a few highly experienced designers and the company was on the cutting edge of the industry. However, with time and growth significant problems have arisen. For example, the company now hires great numbers of new employees but does not maintain an orientation program for the new workers. There is no established way for the experienced workers to share or hand down their knowledge and experience. As a result, the working habits in project teams vary significantly. Also, the increase in one-of-a-kind components is uncontrolled resulting in invalid, inaccurate information between the product development department and the production department.

The current product's structures and the company's work methods are unsustainable. The inconsistency of information and communication between different departments must be solved. The Tekes project was established to work with these and other challenges. The aim was to implement fully configurable products and an information management system into this company, and replace the old order-specific product structures.

5.1.2. Description of the project and involvement of the researcher

The Tekes project began working with the company in autumn 2011 and will continue working as this thesis goes to press in October 2012. The project aims to implement configuration and modularisation into the company's operations and future product structures by developing a product structure information library, a managed database, which will maintain the existing product structure information. Also a PLM system is developed to manage communication and different product life-cycle phases across different departments. This is seen as a solution for many problems the company is currently facing.

Existing partly configurable product structures work as a starting point in developing the future information library and future product modules. Led by Professor Asko Riitahuhta, a group of researchers from TUT specialising in developing modular product architectures contributed to the project by providing their experience and design for configuration methods.

The researchers were involved in mapping and consulting the company's current operations. The work involved a CSL workshop to identify the company's product structures and any related elements such as production processes, organisational structures and core businesses. The aim of the CSL was to develop the company's operations. In addition, TUT researchers provided consultation on the development of the modular architectures, which will replace the current product structures in the future. The author of this research paper was involved in order-delivery-services process structuring and organisational structuring during the spring and summer 2012.

5.1.3. Method of data collection

Data collection involved empirical observation within the workshops and company visits. Results were mainly an outcome from the CSL –workshop and interviews with the company personnel. Also, informal discussions had a role in data collection.

Information was primarily gathered from a CSL-map, to which all the information caught in the workshops was saved. Also, information was recorded in the form of notes from interviews and discussions.

5.2. Comparison of the partly configurable and fully configurable products

This case study was gathered from the data of the project. The author began by mapping the order-delivery process during the project, and continued in the thesis by collecting the missing information from other researchers involved in the Tekes project.

Preparation for the case study included mapping the case product's structure and continued with the mapping of the product's life-cycle, which in this case, was an order-delivery process. Following this, the actual disposition modelling started using the preliminary concept of PLDM as the conceptual framework and the Flow of Product Structuring Knowledge in Manufacturing (Juuti 2012) as a dispositional framework for comparing current product structure to the dispositional scenarios of a fully configurable product structure.

The comparison is limited to three different life-cycle phases and only dispositions in the information flow are captured and analysed.

5.2.1. Mapping the product structure and the product life-cycle

One of the company's most common products was chosen for the case study. Mapping the product's structure involved listing the engineering bill of materials (EBOM), including the list of elements, or components it consists of and the different variables. In figure 5.2, the EBOM represented on the left (highlighted in a red box), lists more than 150 components and variables. In the top row, different customer needs are listed and the matrix represents the relationships between the product elements and customer needs. Different types of relationships are indicated with green, yellow and red colours.

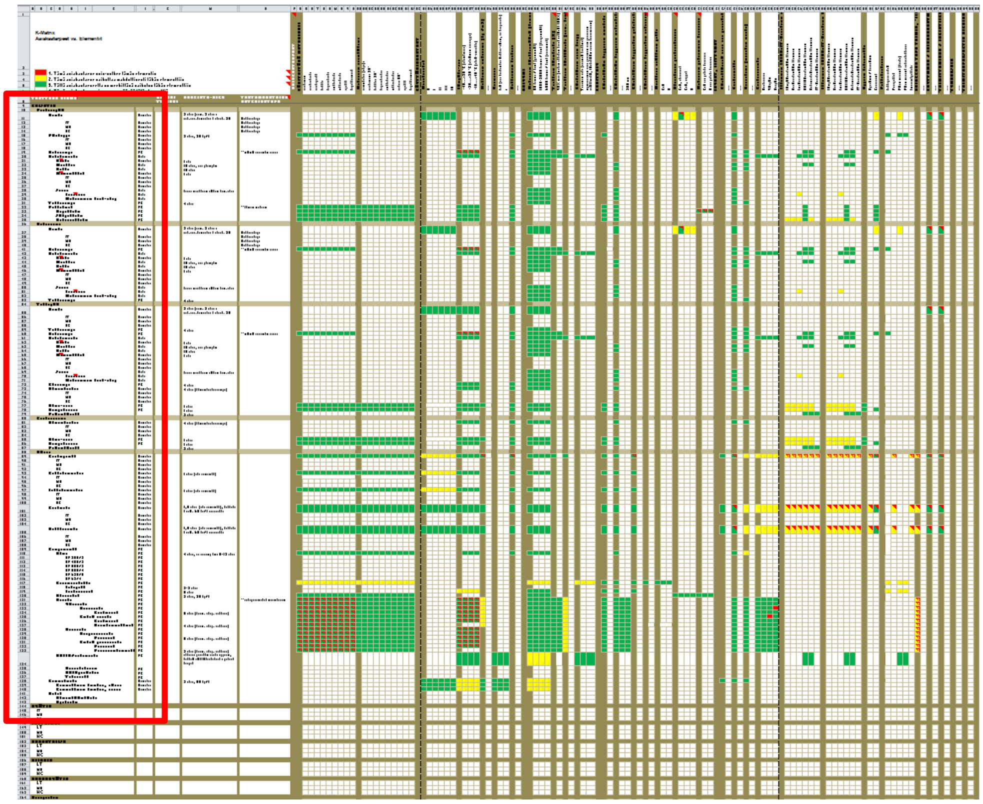


Figure 5.2. *Matrix of Product structure engineering bill of materials and customer needs* (Pakkanen 2012).

Every component and variable was categorised into groups based on whether it was a standard component, a configurable component, sub-contracted, or an order-specific component (one-of-a-kind).

The next step was mapping the product's life-cycle, which in this case is the product's order-delivery process. Figure 5.3 shows the outcome of the modelled order-delivery process.

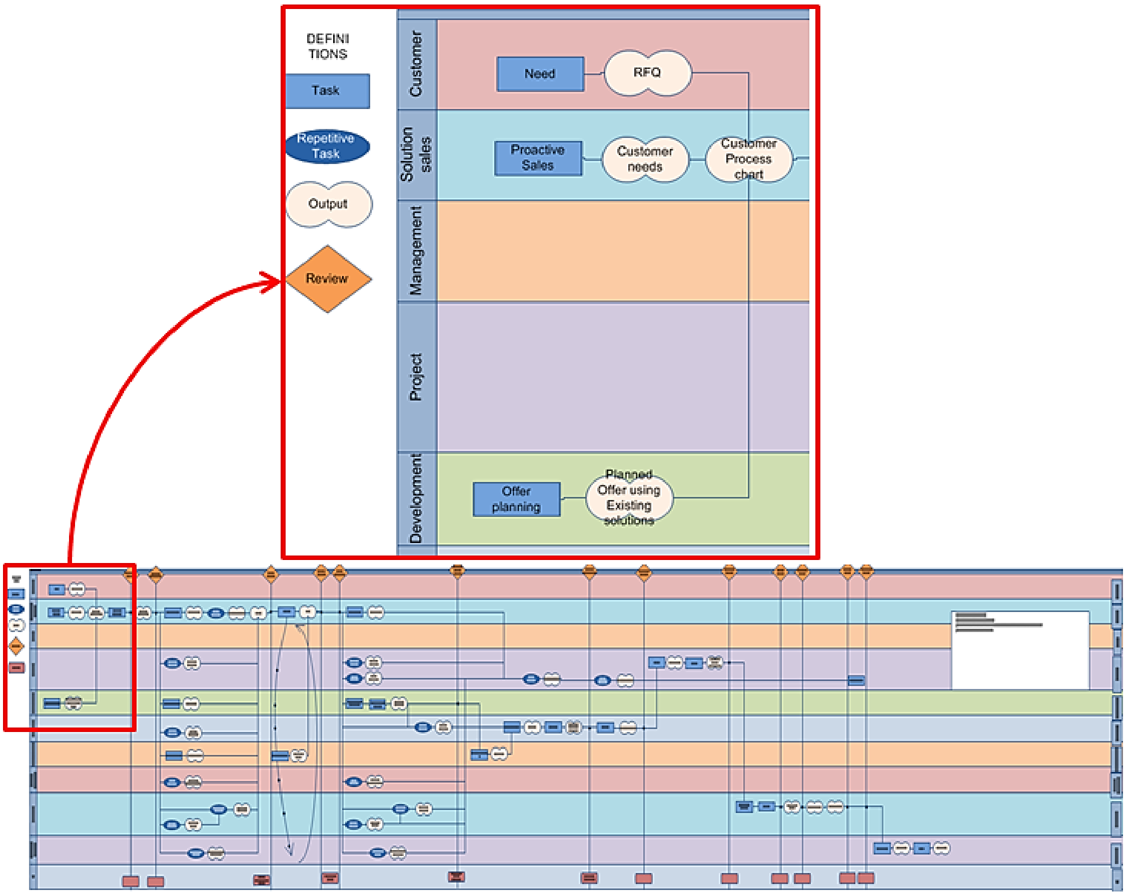


Figure 5.3. *Product's order-delivery process.*

In the figure, the rows illustrated with different colours, indicate organisations involved in the product's life-cycle. The process includes tasks and information outputs, represented with blue and white symbols respectively. The orange symbols indicate the reviewing of tasks, which are the control flow elements.

Preparations were complete after mapping the product's structure and product's life-cycle. Relevant product's characteristics in the case study were the division between standard, partly configurable, configurable and order-specific components. Relevant product lifecycle phases were from order to maintenance within information, work and control flows.

The next phase was modelling the dispositions. In this phase, the dispositions caused by the product's characteristics, or more specifically, order-specific components (one-of-a-kind components), are analysed in three different life-cycle phases: sales, product development and maintenance. These dispositions are then compared to fully configurable product structure scenario.

5.2.2. Dispositions at the point of sale

Company sales people are the only ones involved at the point of sale. Most of the sales people are project leaders that possess some knowledge of the product's structure and have capacity to choose some of the specifications at the point of sale including standard parts, configurable parts, sizes and loads. However, they lack the skills for more detailed, order-specific design at the point of sale. Figure 5.4 illustrates the overview of the dispositions in sales.

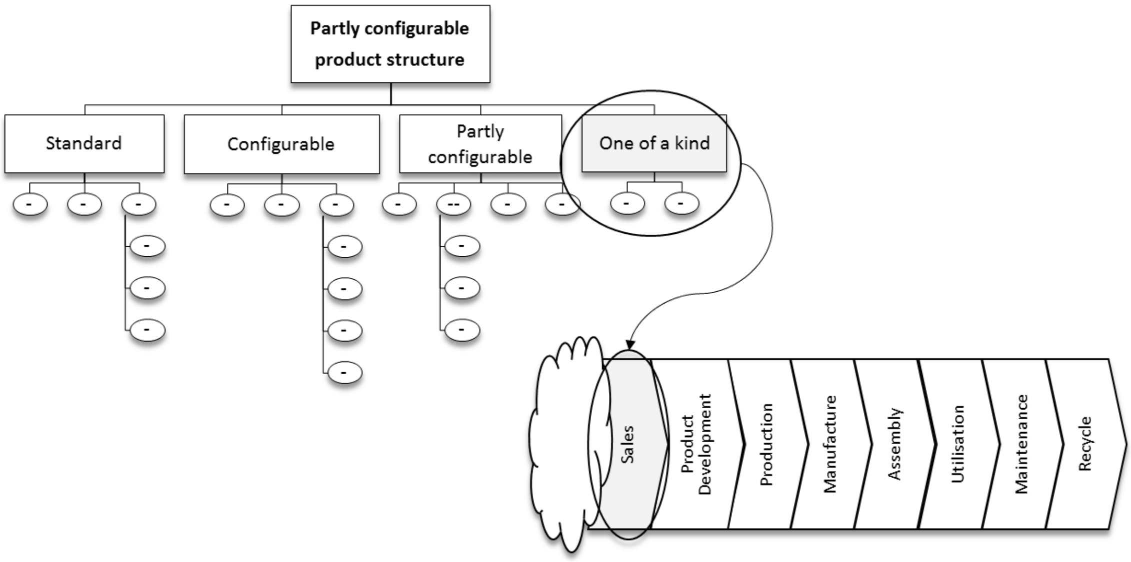


Figure 5.4. *Dispositions between product characteristics and sales in partly configurable product structure.*

A catalogue of standard parts and of some configurable parts exists, but there is no product structure information available from which a design could be reused. These circumstances result with the period of influence existing only at the point of sale, and customers being offered whatever is necessary to complete a successful sale.

It can be concluded that the validity of information in "as offered" depends highly on the salesperson's knowledge and experience. The current integrity of the "as offered" process is thrown into question and effects a growing number of order-specific components.

When compared with a fully configurable product structure, sales persons have a valid product structure information source from where they can choose all solutions. The product structure information source includes all the information on standard components and configurable components. Therefore, with the configurable product, the salesperson is able to specify the product range already at the point sale and the information is integrous.

5.2.3. Dispositions in product development

In the case of partly configurable products, “as offered” requires order-specific design which can be called Order-Specific Product Structure (OSPS). In the company, the validity of information in “as offered” can be questioned, because many of the problems can be traced to inconsistency and invalidity of information. Figure 5.5 illustrates the overview of the dispositions in product development.

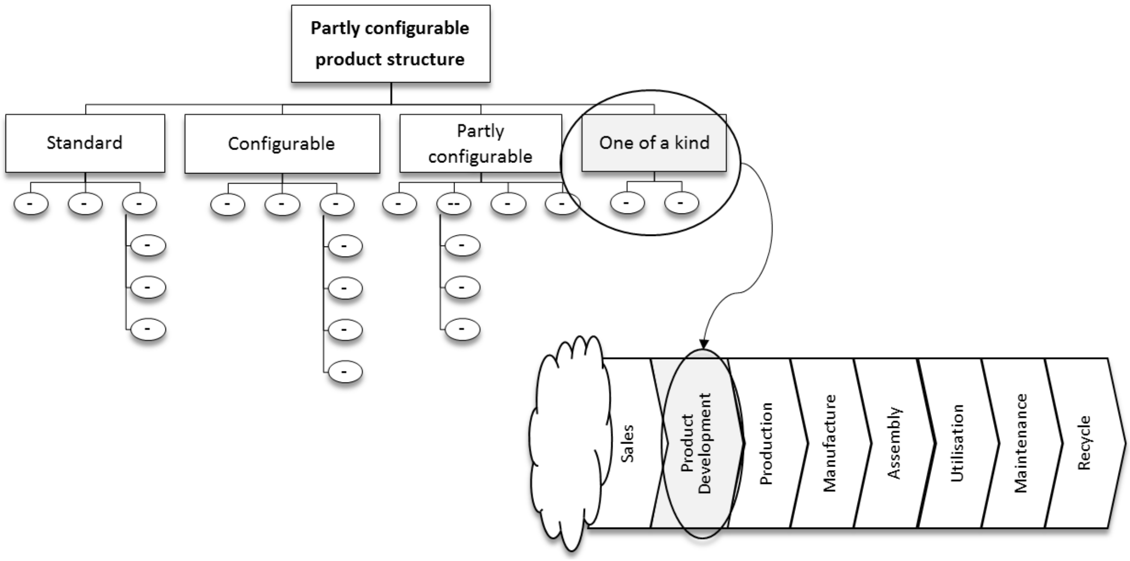


Figure 5.5. *Dispositions between product characteristics and product design in partly configurable product structure.*

In fully configurable product structure, OSPS does not exist, because everything can be chosen from existing product structure information. This means the whole life-cycle phase of delivery specific design can be eliminated and remains highly consistent with “as offered”.

5.2.4. Special situations in delivery specific design

As the Tekes project aims to implement fully configurable product structures in the case company, a significant threat was predicted as an obstacle in the development process for a fully functional information library. The danger was foreseen clearly and therefore included in this thesis.

As the product structure information is maintained over time, new OSPS may be saved as modules within the information library. This is seen a natural development and an update for the library however, the consequences can be devastating if the new design violates any of the following: architecture, interfaces, product structure division logic, modules or configuration information. For example, if an OSPS with the wrong tolerances for connecting modules together is implemented as part of the library, the consequence is that future orders may once again require specific design solutions to counteract violating components.

5.2.5. Dispositions in maintenance

The company's maintenance services are an area of increased growth in the organisation. Currently, the company does not maintain any database or documentation system for old products or deliveries. Limited information can be collected by searching through analogue archives however this is time-consuming and laborious. Once found, the information may not even be consistent with the actual delivery given the possibility of last minute changes to the order. This lack of information impacts various areas, including how services do pricing for maintenance and order spare parts. Currently maintenance requires a complete survey of the product in question before spare parts can be ordered. Figure 5.6 illustrates the overview of the dispositions in maintenance.

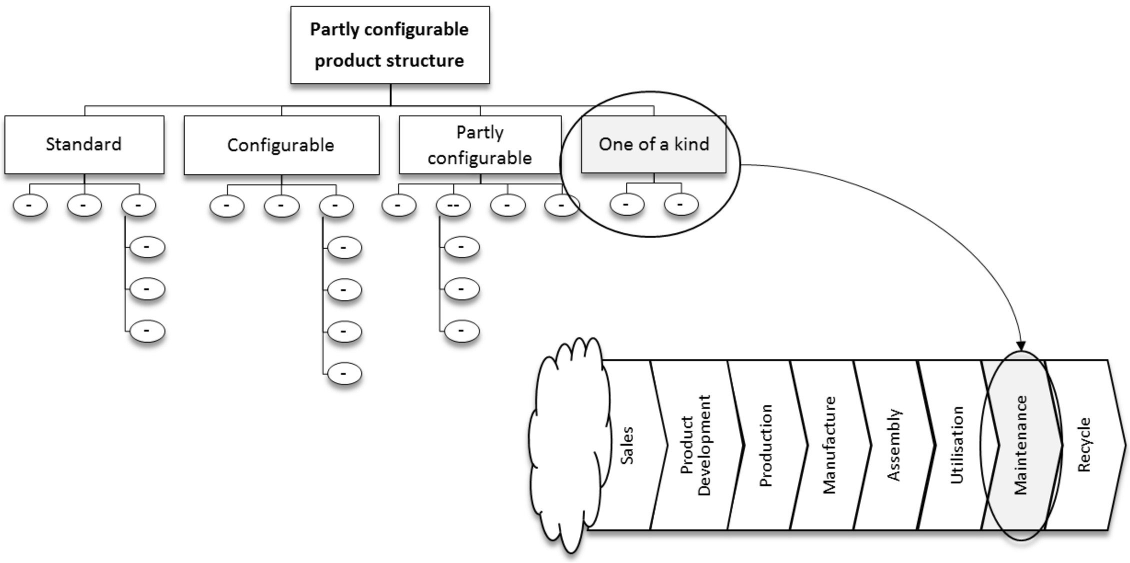


Figure 5.6. *Dispositions between product characteristic and maintenance in partly configurable product structure.*

In fully configurable product structures, maintenance processes use valid information about the past deliveries and current deliveries in a dedicated database. This enables improved quality of service, as maintenance times are reduced and the exact information of previous work is documented.

5.3. Analysis

As the case study was conducted by applying the preliminary PLDM, it was discovered that the process was not completely accurate in practice and did not reflect all the requirements of the real situation. Therefore the preliminary PLDM has to be specified and reworked to fully comprehend the results and recommendations of the case study.

The first finding was that the dispositions inter-relate and interact in two ways, which were not clearly indicated in the preliminary version of the PLDM. For example, the invalid information captured in the dispositions directly affected product's characteristics such as quality, to which a designer can have an influence.

The second finding was that the PDD approach, defined by Weber (2012), was not adequate for the purpose of the case study. What the case study showed, was that the definition of artefact properties had to extend to include desired properties in the life-cycle. In this case, the definition of the properties would include both artefact properties defined by Weber (2012) and artefact life-cycle properties. Artefact life-cycle properties contribute to goal setting in production development. The dispositions modelled showed that the short term problems in invalid information could be affected by changing the process. Thus, the development goals for improved validity of information flow in different life-cycle phases are one example of these artefact life-cycle properties.

In the case study, different life-cycle phases were compared to a scenario in fully configurable product structure. An obvious change in product's characteristics would be to eliminate the use of order-specific components, however this kind of change requires a vast change in a company's operations, resources and in the product's life-cycle, before such a change in product's characteristics could be conducted. The process development was seen as cost effective and direct way to improve both the artefact properties and artefact life-cycle properties.

The analysis results in more comprehensive and complete products and the process development model. The name Property-Driven Development is still tenable in this case, even though the definition is developed from the original Weber (2012). The outcome of PLDM will be presented in the results and recommendations of this thesis. Also, the implementation method is developed to more clearly follow the steps used in the case study.

5.4. Summary of the case study

This study presented an example company, operating in the Finnish manufacturing industry. The case study was done as part of Tekes project - a wider research and consultancy project aimed at implementing fully configurable product structures within the case company.

The case study compared the company's current situation of producing partly configurable products to a scenario of fully configurable product structures. This was done by choosing one of the company's most common products, mapping its structure, life-cycle, and capturing dispositions between both. During the comparison a model for configurable product structures was used to foresee the dispositional effects of fully configurable product structure to the product's life-cycle.

The study was limited to a comparison of only three phases of product's life-cycle and focused on comparing the information flows between the two scenarios.

The study was successful in implementing the scenarios into the PLDM, as all of the elements of the PLDM were utilised and dispositions could be demonstrated. Also, the study successfully answers for the research questions with results and recommendations summarised in the next chapter.

6. RESULTS AND RECOMMENDATIONS

The following results and recommendations are gathered from the case study of Finnish manufacturing industry company whereby dispositions of an existing partly-configurable product are compared to a scenario of a fully configurable product structure. The results address research questions 1, 2, and 3.

6.1. Product Life-cycle Disposition Model

Question 1: What kind of elements a disposition model consists of?

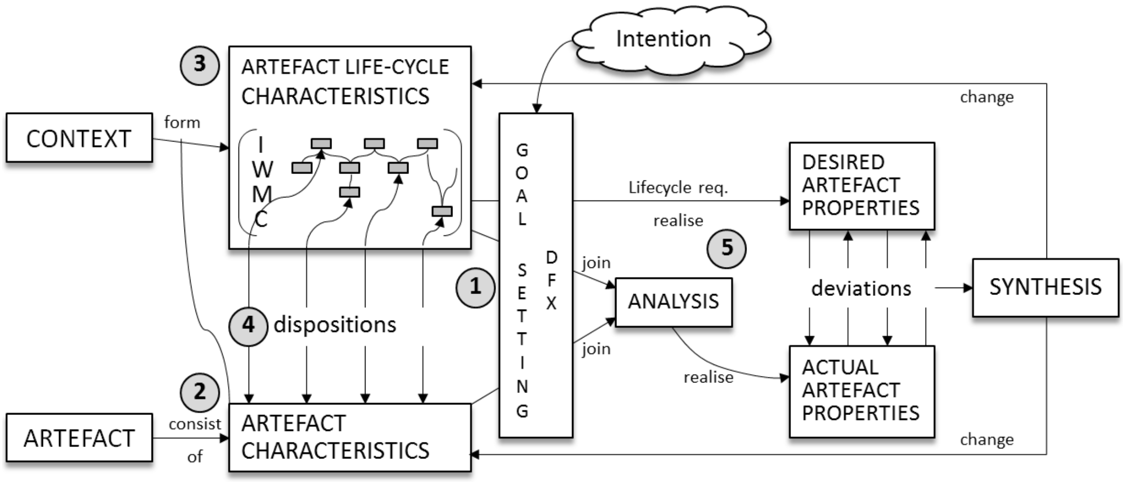


Figure 6.1. *Elements and process of the PLDM.*

In PLDM (figure 6.1), the Property-Driven Development (PDD) process, consists of artefact properties defined by Weber (2012) and artefact life-cycle properties (in figure actual properties). An analysis-synthesis process aims to affect the actual properties reflecting goals to desired artefact properties (5), by acting on artefact characteristics (2) and artefact life-cycle characteristics (3). The context is the environment in which the artefact functions and is examined through the Flow Model. Dispositions are inter-relationships and interaction between artefact characteristics and the artefact life-cycle characteristics and form a central point in the learning cycle. Artefact life-cycle requirements effect the goal setting, or the catalyst of the model.

Question 2: How is a disposition model implemented in practice?

The implementation is divided into 5 steps:

1. Goal setting
2. Mapping artefact characteristics
3. Mapping artefact life-cycle characteristics
4. Modelling dispositions
5. Determining actions through analysis-synthesis process

The steps are numbered in figure 6.1.

Goal setting is the first step, during which the targets of the dispositions study are determined. This includes choosing the DFX approach based on the requirements. Later the goal setting may be defined or changed as relevant dispositions are realised.

Mapping artefact characteristics and artefact life-cycle characteristics is the next step in the implementation. During the mapping process, the focus is on the DFX, chosen during the first step. In all other ways, these steps follow closely the methods presented in the preliminary PLDM, of which more detail description can be read in chapter 4.5.

Modelling dispositions follows the goal setting, and dispositions are captured by answering the questions:

- What kind of dispositions does a specific artefact characteristics have on specific artefact life-cycle characteristics?
- What kind of dispositions do specific artefact life-cycle characteristics have on specific artefact characteristic?

Learning and acknowledging dispositions results in better understanding of the process. This may result in redefining the original goals and targets, before reaching the last step of the implementation, required actions.

The final step is the analysis-synthesis process, during which the actions for change are determined. The actions can be directed to improving either the product or the process in order to achieve the defined, desired properties.

6.2. Results of the case study

Question 3: What is the difference between a fully configurable product family and partly configurable product family?

This chapter provides case study results from information flow point of view. Three life-cycle phases were compared between the two types of product families. The analysed life-cycle phases were sales, product development and maintenance and were selected because they indicate and demonstrate dispositions clearly, as well as the overall product life-cycle.

Partly configurable products are a mixture of standard components, partly configurable components, configurable components and order-specific components (one-of-a-kind). This combination increases unpredictability in offers, since company salesmen always have to tailor solutions for the customers based on their own knowledge and experience. The initial product structure is as a starting point unknown for the salesman since there is no systematic way for the salesman to configure and choose relevant components on site. The problem is that the validity of information is highly dependent on the skills, knowledge and experience of the salesperson.

Fully configurable products can offer solutions based on existing product structure information available in an information library, which includes product structure division logic, module architecture, interface description, information of modules and configuration information. These are also called the criteria for product structure information as presented earlier in chapter 4.4.3. Product structure information provides detailed information on “what to offer” and what has been offered prior. The information is valid and thus all the solutions and parameters can be structured on that knowledge.

Partly configurable products require order-specific product design and therefore can be questioned as to whether the information in what is being ordered is valid. In many cases, order-specific product structures cause invalid information in the product structure; for example a new order-specific component violates some of the criteria in product structure information resulting in changes to configurable components and generating extra work. In a worst case scenario the need for changes are seen not until the components have passed product development phase causing waste work as the components have to be corrected or replaced with correctly designed components.

In fully configurable products, order-specific product structure is unnecessary, therefore the whole order-specific design phase can be eliminated from the life-cycle process. If in the information library product structures do not violate one of the criteria of product structure information, information remains valid throughout the order-delivery process. Violation of the information results in delivery specific design, which should be seen as dangerous threat for the development of the information library.

Consequences are seen in future life-cycles if the new order-specific component is included as an element within the library and later violates some of the configuration criteria. For example, if the new design does not support the existing module architecture, changes and problem solving is required in other components to overcome issues with integrating modules. These kinds of order-specific components result in invalid information.

Regarding maintenance services, the difference between partly and fully configurable products is in quality of information. As fully configurable product information is regarded as valid, companies producing partly configurable products will wrestle with questions regarding information availability, consistency and validity. Valid information in maintenance services has potential to ease costs of servicing and managing product spare parts.

6.3. Recommendations

These recommendations are a summary of conclusions from the case study and its results. The recommendations cover the three phases of product's life-cycle, and pertain to the current situation of the case company. These recommendations can be generalised to all companies producing partly configurable products.

Valid information for product structures types offered to customers is achievable when salespeople and engineers are both involved at the point of sale. Engineers have the ability and tools to design and make order-specific product structures on the field while at the point of sale. This encourages reuse of existing product information as engineers are steered toward using available information instead of designing order-specific components.

In order to have valid information during product development a product structure blueprint (Timo Lehtonen et al. 2011) should be generated, making the design rationale visible. In addition, order-specific product structures will benefit from a quality assurance –check-list to assure the new design does not violate existing product structure information.

In order to avoid the threat of order-specific product structure violating the information library, the company needs to manage the product structure information. Part of the management system, can include an information library where interfaces and modules have IDs, version control, and responsible owners. Also, the information library must consist of approval process for new elements and when updating older elements.

Maintenance services require systematic practice to update and manage product information of delivered products. This means that all of the product's delivered elements should be in the same database and be easily accessible for maintenance services. Information in the database is controlled with the same principles as in the product structure information library.

6.4. Summary of results and recommendations

Companies should focus in actions that improve validity of information throughout the order-delivery processes. The case study indicates that smaller improvements can be made to improve the validity of information, but the biggest influence comes from reducing, and then eliminating, the need for one-of-a-kind components in the order-delivery process.

Consequences of invalid information are seen in product characteristics and throughout the product life-cycle. Invalidity of information causes costs, delays, poor quality and many other challenges in manufacturing. With the help of PLDM companies are able to recognise unwanted dispositions that cause invalid information.

7. DISCUSSION

In this chapter, the significance of the research and the limitations are discussed as well as recommendations for further research. The significance of the research is discussed in relation to its contribution to the Finnish manufacturing industry and to the field of Design Science.

This research was conducted in the context of the Finnish manufacturing industry with the case study featuring a typical, project-oriented manufacturing company in Finland. The case study examined a specific set of challenges surrounding partly configurable product families, which was the case company's primary mode of operation. Analysis revealed that the company, due to its growth and subjective viewpoint, lacked full understanding of the effect their mode of operation was having on the overall business and its potential effect on sustained growth of the company.

The case study brought to surface the importance of the industry's need to be aware and understand also alternative modes of operation and the possibilities for improved change. Manufacturing businesses might not realise the need for this knowledge however for the case company, the improvement for their business operations was seen when comparing their current product structure and its operations to a scenario of fully configurable product and its operations. This also functions as an educational element for providing knowledge of product configuration and modularisation to companies.

In addition, the PLDM conceptual framework is fundamentally designed to reveal the sub-conscious relationship between a product's characteristics and a product's life-cycle. This sub-consciousness was reinforced when examining the company involved in the case study. Also, this acknowledgement is present in many other companies within Finnish manufacturing industry according to the broader experience of the IPPD research group's body of knowledge at TUT.

The PLDM is also the significant contribution to Design Science since it emphasises the significance of a product structure's influence to a company's overall operations. At its foundation are theories that contribute to Design Science such as Soft Systems Thinking (Checkland 1985), Theory of Dispositions (Olesen 1992) and Property-Driven Development (Weber 2012).

The novelty of the model occurs in three different levels of abstraction. Firstly, research introduced an explanatory model, which pictures artefact knowledge in an interaction and interrelationship in a wider context; a system within a system. Secondly, this artefact is further detailed in artefact (product) structure and the broader context is detailed in a Flow model. Thirdly, the product structure is identified in product characteristics, which in this case are demonstrated with characteristics of a partly configurable and fully configurable product. The Flow model further details information, material and work flows in a partly configurable and fully configurable product's life-cycle.

The thesis provides the initial conceptual framework for PLDM, therefore it is limited to the manufacturing industry and brownfield products, in which available data can be identified from existing products' structures and products' life-cycles. Some of the elements in the model require more research and definition in the future since the scope of this research did not allow for more thorough investigation of these elements. For the purposes of this research, one of the areas that do not get enough attention was the research done in design rationale, as the thesis did not cover research done specifically in this area and does not reveal how the design rationale can be easily exemplified. It is seen as one of the core outcomes of the PLDM model, therefore it should to be explored better in future research. The other area that requires more definition is the artefact life-cycle, which combines a broad area of elements under one umbrella. It is reasonable in the future to define this area in more detail as, for example, all of the external influences affecting the life-cycle of an artefact are also included in this element.

The implementation of disposition modelling is aligned with the previous research done within the TUT research group. The implementation consisted of a CSL-framework (Lehtonen 2007) as a starting point for identifying relevant data to the model including product structures, and product life-cycle processes and characteristics. CSL provides a framework which refines the focus, and is also useful in DFX modelling as there is always a catalyst for change when modelling dispositions.

The Flow model is also used as a core depiction method to identify and understand relevant elements of the life-cycle. The thesis has provided a few examples of past research projects at TUT in which the Flow model has been utilised. (Lehtonen 2012) This is the first time the Flow model has been used to depict the product life-cycle as a whole. In previous cases, the Flow model has been limited to project management in product development and production.

Within dispositional thinking PLDM provides a new framework where dispositions are actively utilised. According to Olesen (1992), dispositions occur between activity based characteristics, however in PLDM a disposition is seen as an interaction and an inter-relationship between artefact characteristics and artefact life-cycle. The first definition can be identified as activity based and the latter, artefact oriented. Dispositions in both cases are subject to natural laws and appear even without acknowledging them. Dispositions in both definitions are challenging to identify and depict.

Property-Driven Development (Weber 2012) is a key starting point in constructing PLDM, as the artefact properties and the deviations between requirements and existing properties direct the cyclic actions. The PLDM uses PDD at a broader scale, introducing PDD's process elements as part of its conceptual framework, also taking into consideration life-cycle aspects. PDD is used as a base for the concept to provide analysis and synthesis to both, artefact characteristics actions and life-cycle characteristics actions. One of the fundamental differences between these two models is that in PLDM requirements are changing and evolving because of the dispositions happening in the system, whereas PDD does not consider changing requirements during the process.

The limitations of the research had an effect on the final results. The time line limited considering the scope of the study. Time limits did not allow for an in-depth analysis, which in retrospect, the area of study would benefit from it.

The research also relied on a single case study, which means that the research is not able to make generalised statements. Furthermore, the case study was narrowed down to examine three phases of case product’s life-cycle, in which only the dispositions within information flow were explored. However, the case study was expected to function only as an initial demonstration of the research areas and in this context it succeeded in providing an interesting and practical scenario.

Case studies are seen as the next phase within the broader research project. Future studies should examine all of the elements of the Flow model. This would involve the four flows of work, information, material and control to be depicted and analysed during the mapping process of product development, and during the disposition modelling phase. Also case studies should provide a wide variety of examples across the manufacturing industry. This way the case study covers all of the potential of the conceptual framework.

The research was also limited by external circumstances, which involved the changing direction of the research. This affected the ability to address the entire scope of the research and ultimately changed the final focus of the thesis.

The research process was conducted using the Finnish language, which linguistically differs significantly from English. Writing the research paper in English has brought up limitations within research process. Finding the exact terms and definitions in English that accurately mirror the original Finnish technical and conceptual language used as part of this study has, in retrospect, been a significant challenge.

8. CONCLUSION

This thesis has described differences of characteristics and behaviour between partly configurable product structures and fully configurable product structures, in three life-cycle phases. By doing so started a conversation of challenges faced by partly configurable product families in the Finnish manufacturing industry. The research process was done by developing a Product Life-cycle Disposition Model (PLDM), a conceptual framework, which was then implemented in a case study with a Finnish manufacturer. The results of the case study showed problems that a partly configurable product structure faces in comparison to fully configurable product structure within the product's life-cycles. Finally, recommendations for actions in the company were drawn from the comparison.

Theory basis and state of the art provided a starting point for developing the PLDM framework. Influential theories for PLDM were Soft Systems Thinking, and theories within Design Science. The influences within the state of the art in structuring PLDM were product life-cycle modelling and Flow model. One of the results was to structure the initial elements of the model, which was tested through the case study. The implementation method followed the principles of the preliminary PLDM.

The case study involved examining one of a company's products by viewing it through the PLDM conceptual framework. The preparatory work consisted of mapping the relevant characteristics of the partly configurable product. After this, the product's order-delivery process was mapped with the principles of the Flow model. This represented the mapping of product's life-cycle. Dispositions between the product's characteristics and product's life-cycle were modelled within three life-cycle phases, sales, product development and maintenance. The dispositions were then compared with a scenario of fully configurable products. The scenario was based on the map of The Flow of Product Structuring Knowledge in Manufacturing (Juuti 2012). The results and recommendations were drawn from the data and a retrospective analysis of the case study.

From the analysis of the case study, the final version for PLDM was constructed. It resembles more the practical situation applied in the case study. Compared with the initial PLDM structured from the literature review, the final version was broadened to also include the product life-cycle actions within the analysis and synthesis process. This way the PLDM changed from focusing on product's technical properties and behaviour to also include a product's life-cycle properties and considering actions in changing product life-cycle characteristics according to changing requirements in context.

The final model was based on the hypothesis that product structure and its characteristics have interactions and an interrelationship with a product life-cycle's characteristics. These relationships are called dispositions and are subject to natural laws, so they happen purposefully or unaware. They also occur in both directions as opposed to the preliminary PLDM, which only considered disposition from product structure to product life-cycle, so product structure affects the product life-cycle and life-cycle affects the product structure.

The case study also clarified the analysis and synthesis process of PLDM. The actions in changing product's technical specifications were not seen as adequate. The case study indicated that instead of changing product characteristics, recommendations should be drawn to product life-cycle characteristics, for example for the production process. This way the PLDM model contributes to the integrated product and production system.

The order-specific product structure in partly configurable product demands more working stages because of the one-of-a-kind components, and the analysed information flow indicated that the invalid information of the partly configurable product structure is subject to many unnecessary problems during the product life-cycle. In the case study, the comparison of the fully configurable product scenario was seen to be a good direction to develop the company's product families and operations, but any actions for improving the validity of information during the order-delivery within existing operations were seen effective way to improve company's competitiveness.

The case study confirmed the PLDM and its possibilities in modelling dispositions and using it as a conceptual framework for helping the design reasoning. The PLDM has the potential to describe the design rationale of a product, as long as the interpretation is supported with adequate software and description methods such as diagrams and graphs. The novelty of the research comes from combining both the artefact knowledge and artefact life-cycle knowledge in a broader context. The PLDM is seen as a platform to which a support tool could be developed, where integrated product and production development can be conducted using a chosen DFX approach. The development then can be directed to reduce unnecessary work phases, and the product and the process developed to a leaner environment.

REFERENCES

Andreasen, M.M., 1980. Machine Design Methods Based on a Systematic Approach - Contribution to a Design Theory. Lund Institute of Technology.

Andreasen, M.M., Hansen, C.T. & Mortensen, N.H., 1997. On the Identification of Product Structure Laws. In Proceedings of the 3rd WDK Workshop on Product Structuring. Delft University of Technology.

Andreasen, M.M., Hansen, C.T. & Mortensen, N.H., 1996. The Structuring of Products and Product Programmes. In Proceedings of the 2nd WDK Workshop on Product Structuring, The Laboratory for Production Engineering. Delft University of Technology.

Andreasen, M.M. & Hein, L., 1987. Integrated Product Development, Springer-Verlag London.

Birkhofer, H. & Wäldele, M., 2009. The Concept of Product Properties and its Value for Research and Practice in Design. In Proceedings of 17th International Conference on Engineering Design (ICED 09), Stanford University, Palo Alto. Glasgow: Design Society, pp. 227–238.

Blessing, L.T.M. & Chakrabarti, A., 2009. DRM, a Design Research Methodology. In London: Springer. Available at: http://www.springerlink.com/index/10.1007/978-1-84882-587-1.

Blessing, L.T.M., Chakrabarti, A. & Wallace, K.M., 1995. An overview of descriptive studies in relation to a general design research methodology. In E. Frankenberger & P. Badke-Schaub, eds. Designers: The Key to Succesful Product Development. Springer-Verlag, pp. 56–70.

Blessing, L.T.M., Chakrabarti, A. & Wallace, K.M., 1992. Some issues in engineering design research. In N. Cross, ed. OU/SERC Design Methods Workshop. The Open University, Milton Keynes.

Borowski, K.H., 1961. Das Baukastensystem in der Technik, Springer-Verlag.

Brady, T. K. (2002): Utilization of Dependency Structure Matrix Analysis to Assess Complex Project Designs. In: Proceedings of DETC´02: ASME 2002 Design Engineering Technical Conferences & Computers and Information in Engineering Conference. Montréal: ASME.

Browning, T. R., 2001. Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. IEEE Transactions on Engineering Management, 48(3), pp. 292-306.

Checkland, P.B., 1985. From Optimizing to Learning : A Development of Systems Thinking for the 1990s. Journal of the Operational Research Society, 36(9), pp.757–767. Available at: http://www.jstor.org/stable/10.2307/2582164.

Checkland, P.B., 1981. Systems Thinking, Systems Practice. In Chichester: Wiley.

Checkland, P.B. & Haynes, M.G., 1994. Varieties of systems thinking : the case of soft systems methodology. System Dynamics Review, 10, pp.189–197. Available at: http://web.ebscohost.com/ehost/pdfviewer/pdfviewer?sid=fd01a4b5-947b-4a96-b057-e43db4c85f7e%40sessionmgr114&vid=2&hid=112.

Checkland, P.B. & Scholes, J., 1990. Soft Systems Methodology in Action, Chichester: Wiley.

Danilovic, M., & Browning, T., 2007. Managing complex product development projects with design structure matrices and domain mapping matrices. International Journal of Project Management, 25(3), pp. 300-314.

Davidz, H., 2006. Enabling Systems Thinking to Accelerate the Development of Senior Engineerings. Massachusetts Institute of Technology. Available at: http://onlinelibrary.wiley.com/doi/10.1002/sys.20081/pdf.

DSMweb, 2011. International portal for DSM. TUM. Available at: http://www.dsmweb.org [Accessed October 27, 2012]

Fujimoto, T., 2007. Competing to Be Really, Really Gool. The Behind-the-Scenes Drama of Capability Building Competition in the Automobile Industry, International House of Japan.

Gopsill, J.A., Mcalpine, H.C. & Hicks, B.J., 2011. Learning From the Lifecycle: The Capabilities and Limitations of Current Product Lifecycle Practice and Systems. In Proceedings of International Conference on Engineering Design, ICED11. Kopenhagen: Design Society Glasgow.

Grote, K.-H., Walo, M.L. & Miller, J.L., 1998. Manufacturing and product development in the USA , in particular in the Los Angeles Basin and the strategic training and implementation of high manufacturing technology. Integrated Manufacturing Systems, 9(4), pp. 228–235.

Halonen, N., Juuti, T & Luostarinen, P., 2012. DSM Made Easy. In Proceedings of the 12th International Design Conference. Dubrovnik: University of Zagreb, pp. 1445–1454.

Hepperle, C. et al., 2011. Consideration of Goal Interrelations in Lifecycle-oriented Product Planning. In Proceedings of International Conference on Engineering Design, ICED11. Kopenhagen: Design Society Glasgow.

Hubka, V. & Eder, E., 1996. Design Science, London: Springer-Verlag London.

Hubka, V. & Eder, E., 1988. Theory of Technical Systems, Berlin: Springer-Verlag.

Huhtala, P. & Pulkkinen, A., 2009. Tuotettavuuden kehittäminen - Parempi tuotteisto useasta näkökulmasta, Teknologiateollisuus Ry.

Juuti, T., 2012. Research Fellow, Tampere University of Technology. Tampere. Interview 6.7.2012.

Juuti, T, 2008. Design Management of Products with Variability and Commonality – Contribution to the Design Science by elaborating the fit needed between Product Structure , Design Process , Design Goals , and Design Organisation for Improved R&D Efficiency. Tampere University of Technology.

Juuti, T. & Lehtonen, T., 2006. Using Multiple Modular Structures in Delivering Complex Products. In Proceedings of NordDesign. Reykjavik.

Kasanen, E., Lukka, K. & Siitonen, A., 1993. The constructive approach in management accounting research. Journal of Management Accounting Research, 5, pp.243–264.

Kiritsis, D., Bufardi, A. & Xirouchakis, P., 2003. Research issues on product lifecycle management and information tracking using smart embedded systems. Advanced Engineering Informatics, 17(3-4), pp.189–202.

Kohn, A., & Lindemann, U., 2009. Combination of Algorithms and Visualization Techniques Considering User Requirements – A Case Study. In Proceedings of 11th International DSM Conference. Munich: Carl-Hanser-Verlag, pp. 207–220.

Koho, M., 2010. Production System Assessment and Improvement A Tool for Make-to-Order and Assemble-to-Order Companies. Tampere University of Technology.

Kolb, D., 1984. Experiential learning: experience as the source of learning and development, Englewood Cliffs, New Jersey: Prentice Hall.

Koskela, L., 2000. An exploration towards a production theory and its application to construction. Technical Research Centre of Finland.

Lamb, C.T. & Rhodes, D.H., 2009. Collaborative systems thinking: Uncovering the rules of team-level systems thinking. In 3rd Annual IEEE Systems Conference. Ieee, pp. 413–418.

Lehtonen, T., 2007. Designing Modular Product Architecture in the New Product Development. Tampere University of Technology.

Lehtonen, T. Juuti, T., Pulkkinen, A. & Riitahuhta, A., 2003. Dynamic Modularisation – a Challenge for Design Process and Product Architecture. In Proceedings of International Conference on Engineering Design, ICED03. Stockholm: Design Society Glasgow.

Lehtonen, T., Pakkanen, J., Juuti, T., Vanhatalo, M. & Becker, I., 2012. Achieving Integrated Product and Production Development with Knowledge Creation and Flow Model. In Proceedings of Conference on Flexible Automation and Intelligent Manufacturing FAIM 2012. Tampere University of Technology.

Lehtonen, T., Pakkanen, J., Lanz, M. & Tuokko, R., 2011. Brownfield Process for Developing of Product Families. In Proceedings of International Conference on Engineering Design, ICED11. Kopenhagen: Design Society Glasgow.

Lehtonen, T., Pakkanen, J., 2008. Flow model of production tasks in boat manufacturing, VETOMO project. Tampere University of Technology. Unpublished work.

Lindemann, U., Maurer, M., & Braun, T., 2009. Structural Complexity Management - An Approach for the Field of Product Design. Springer Berlin Heidelberg.

Lukka, K., 1991. Laskentatoimen tutkimuksen epistemologiset perusteet. Liiketalouden aikakauskirja, 40(2), pp.161–186.

Olesen, J., 1992. Concurrent Development in Manufacturing - Based on Dispositional Mechanisms. Institute for Engineering Design, The Technical University of Denmark.

Pakkanen, J., 2012. Dependency matrix of engineering bill of materials and customer re quirements, Tekes project. Tampere University of Technology. Unpublished work.

Pakkanen, J., Becker, I., Lehtonen, T. & Juuti, T., 2012. Capturing The Flows of the Product Process. In Proceedings of the 12th International Design Conference. Dubrovnik: University of Zagreb, pp. 1557–1566.

Richmond, B., 1993. Systems Thinking: Critical Thinking Skills for 1990's and Beyond. System Dynamics Review, 9(2), pp.113–133.

Shin, J.-H. Jun, H.-B, Kiritsis, D. & Xirouchakis, P., 2010. A decision support method for product conceptual design considering product lifecycle factors and resource constraints. The International Journal of Advanced Manufacturing Technology, 52(9-12), pp.865–886. Available at: http://www.springerlink.com/index/10.1007/s00170-010-2798-9.

Steward, D. V., 1981. Design structure system: A method for managing the design of complex systems. IEEE Transactions on Engineering Management, 28(3), 71–74. Available at: http://www.csa.com/partners/viewrecord.php?requester=gs&collection=TRD&recid=0092658CI

Suh, N.P., 1990. The Principles of Design, Oxford University Press.

Tiihonen, J., Soininen, T., Männistö, T. & Sulonen, R., 1996. State-of-the-practice in product configuration – a survey of 10 cases in the Finnish industry. In Knowledge intensive CAD. p. 352. Available at: http://reference.kfupm.edu.sa/content/s/t/state_of_the_practice_in_product_con_sur_2409629.pdf.

Tilstra, A., Campbell, M., Wood, K., & Seepersad, C., 2010. Comparing Matrix-Based and Graph-Based Representations for Product Design. In Proceedings of the 12th

International DSM Conference – Managing Complexity by Modelling Dependencies. Munich: Carl-Hanser-Verlag, pp. 195–206.

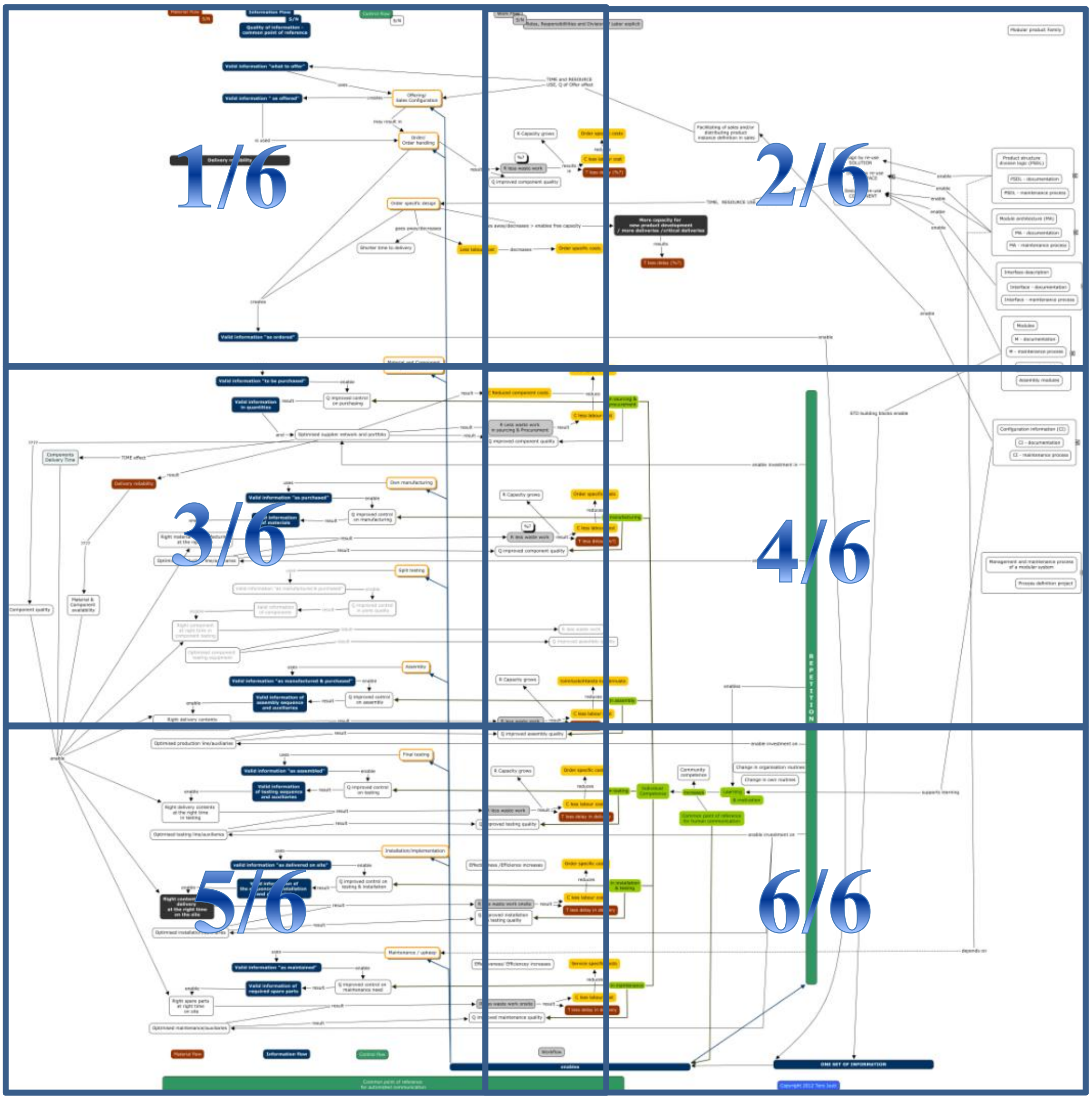
Weber, C., 2012. Idea – Invention – Innovation : Strategies, Approaches, Research Challenges. In Proceedings of the 12th International Design Conference. Dubrovnik: University of Zagreb, pp. 1265–1274.

Weber, C., 2005. What is "Complexity"?. In Proceedings of the 15th International Conference on Engineering Design, ICED05, Melbourne: Design Society Glasgow.

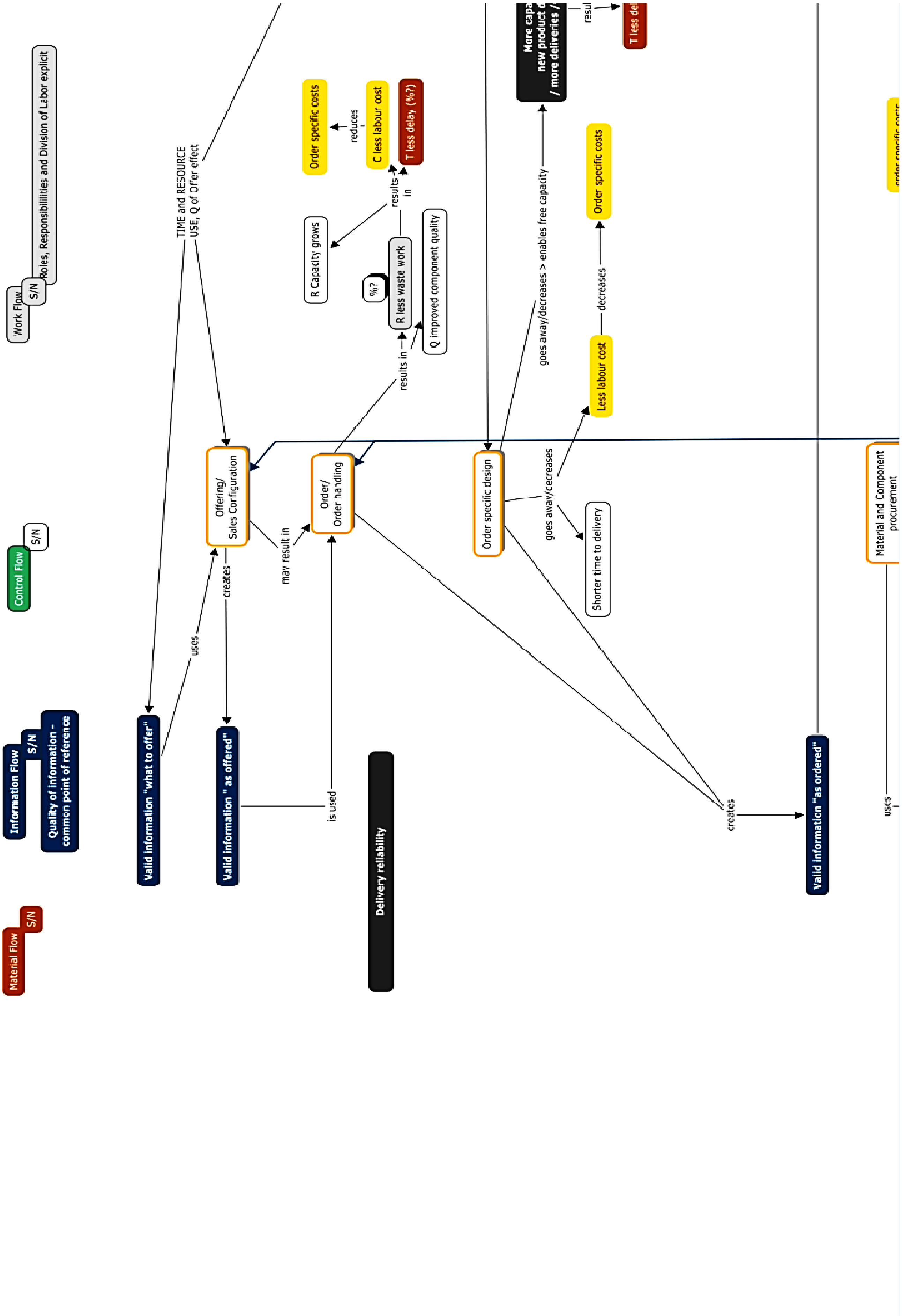
Zexian, Y. & Xuhui, Y., 2010. A Revolution in the Field of Systems Thinking — A Review of Checkland ' s System Thinking. Systems Research and Behavioral Science, 27, pp.140–155. Available at: http://onlinelibrary.wiley.com/doi/10.1002/sres.1021/pdf.

APPENDIX 1: THE FLOW OF PRODUCT STRUCTURING KNOWLEDGE IN MANUFACTURING

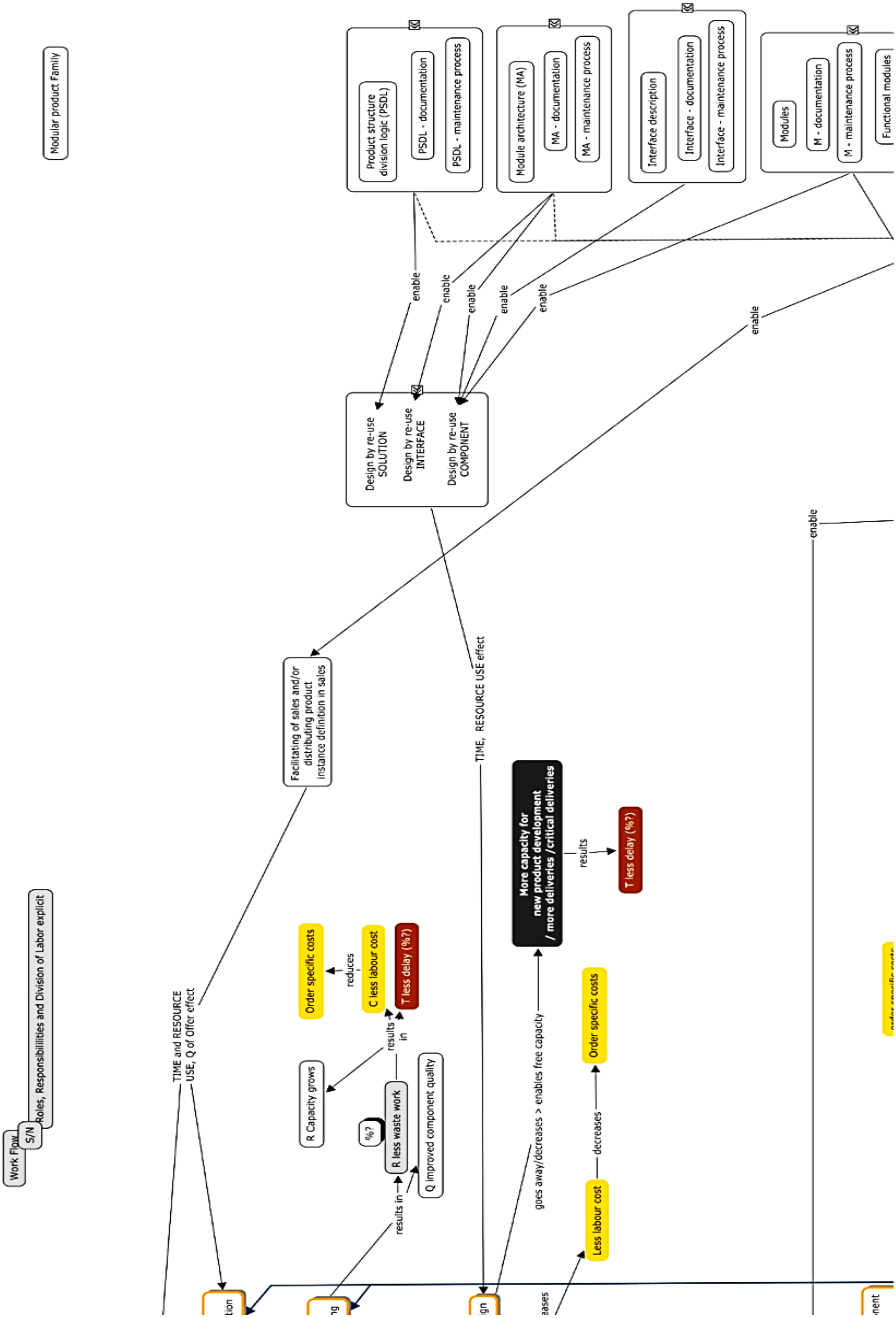
OUTLINE:



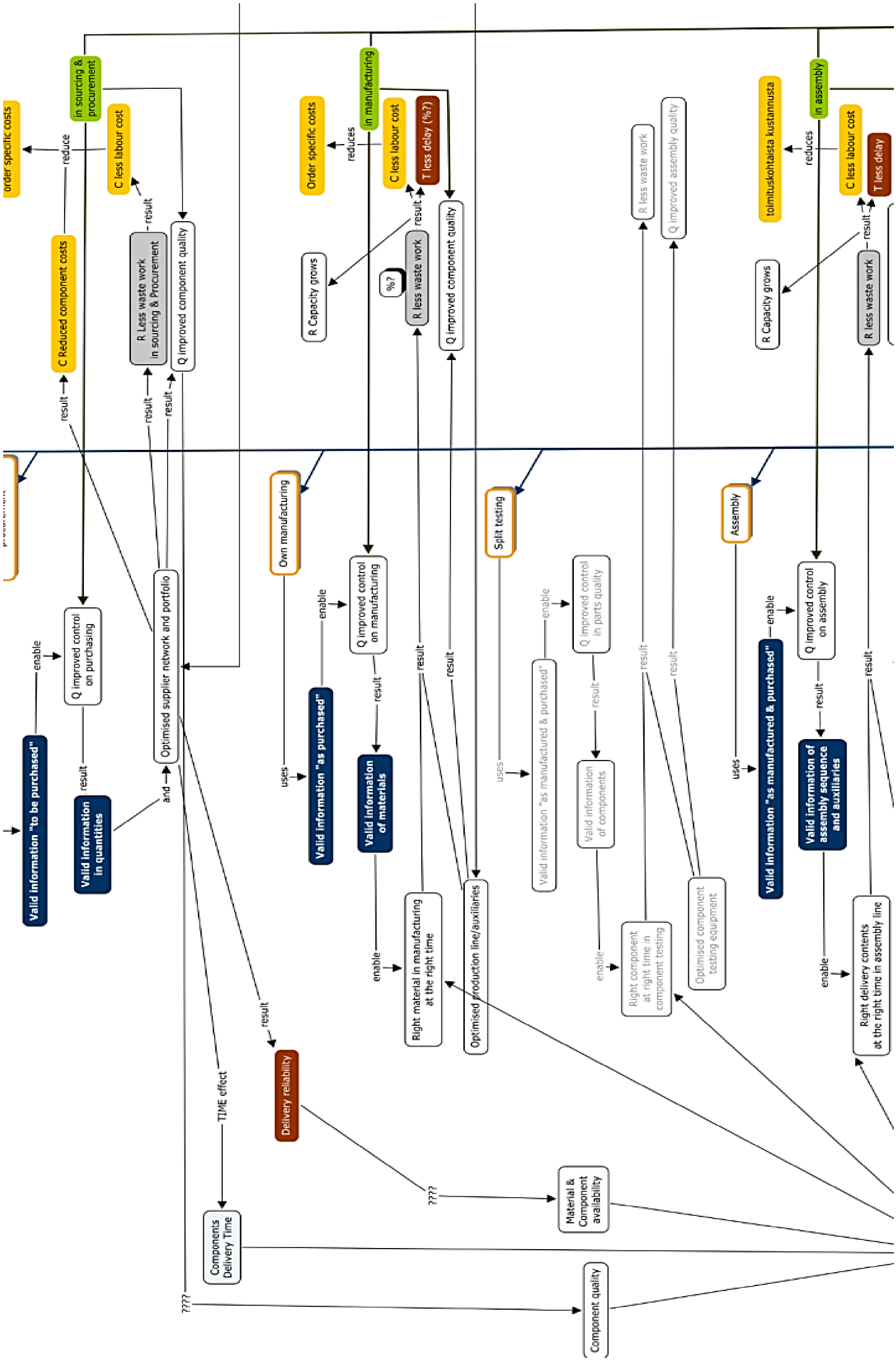
APPENDIX 1: 1/6



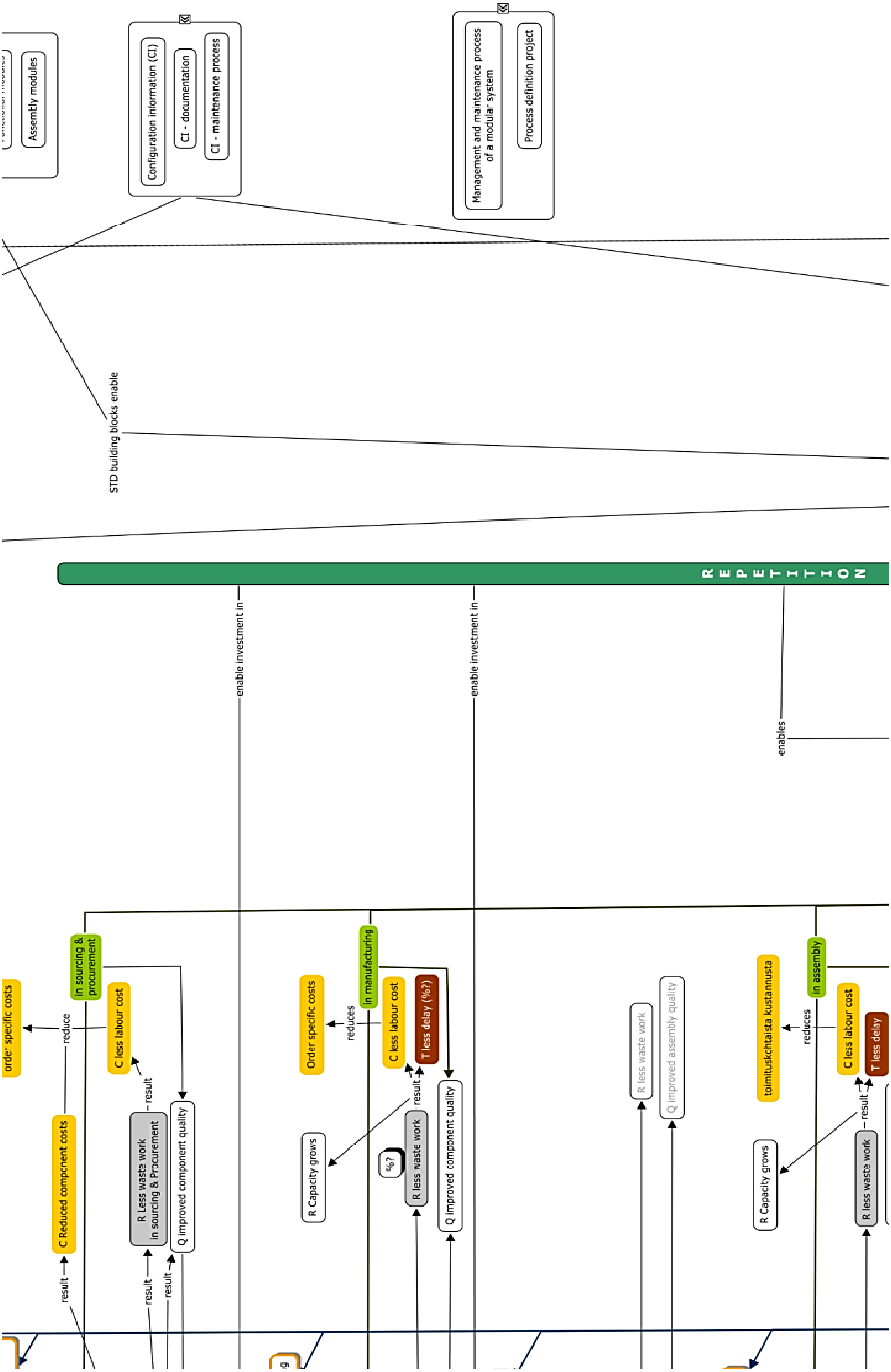
APPENDIX 1: 2/6



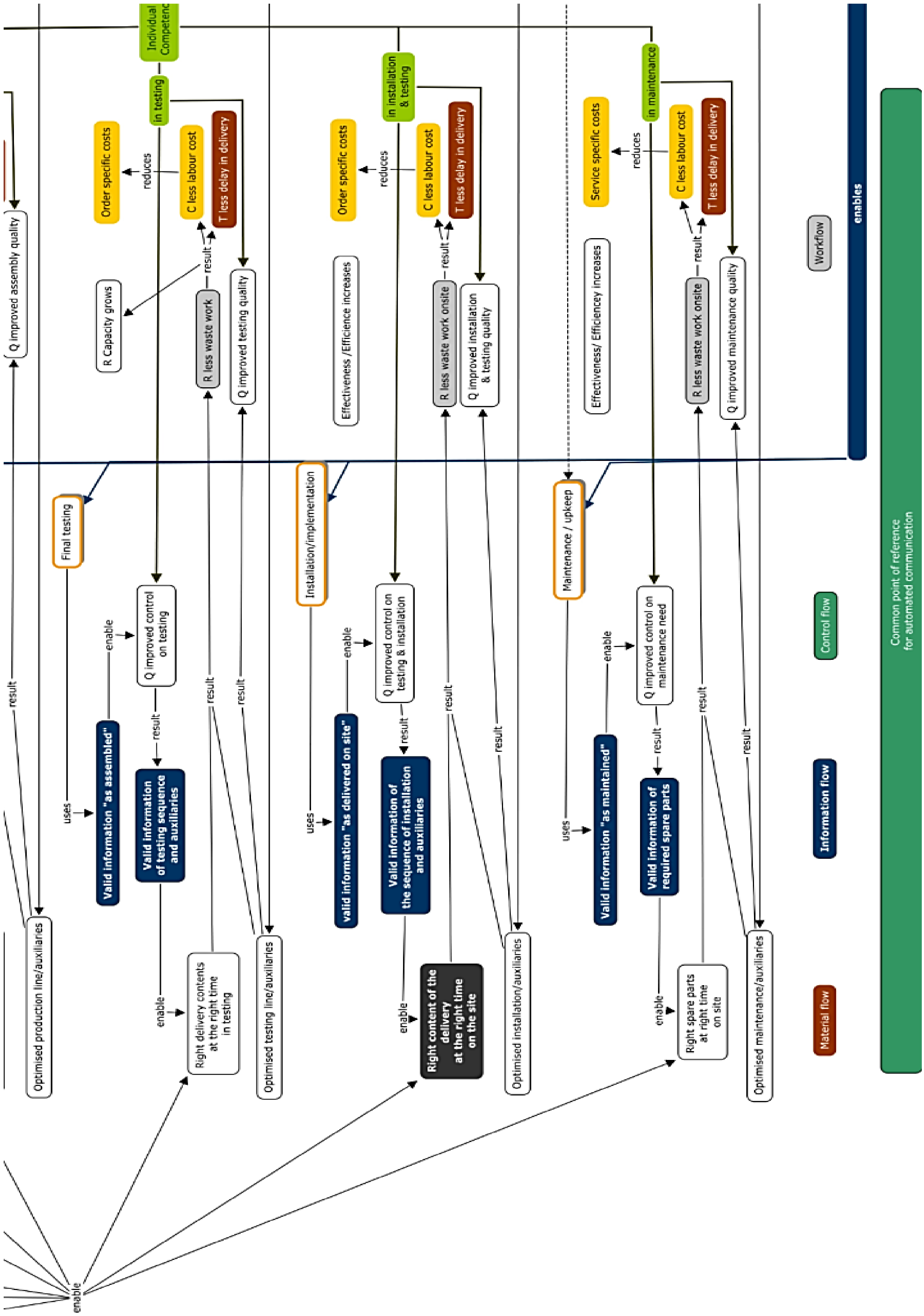
APPENDIX 1: 3/6



APPENDIX 1: 4/6



APPENDIX 1: 5/6



APPENDIX 1: 6/6